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POTENTIAL OF COMPOSITE MATERIALS TO REPLACE CHROMIUM, COBALT AND MANGANESE IN CRITICAL APPLICATIONS

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POTENTIAL OF COMPOSITE MATERIALS
TO REPLACE CHROMIUM, COBALT AND MANGANESE
IN CRITICAL APPLICATIONS

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EXECUTIVE SUMMARY

This study provides an analysis of the potential for substituting composite materials for critical materials in the jet engine, automotive and oil/gas equipment industries. It includes an assessment of the technical, economic and institutional factors contributing to direct and indirect substitution in these industries.

In the jet engine industry, substitution towards composite materials is expected to be performance and market driven. Cost considerations for jet engine materials will be of secondary importance relative to the overall cost of the engine.

Tungsten wire reinforced superalloys (W/FeCrAlY) have a near-term potential for directly substituting for superalloys in jet engine blades, vanes and discs in the event of a crisis. Otherwise, W/FeCrAlY is not expected to be introduced by industry into jet engines components. W/FeCrAlY can increase some performance charateristics of the engine, though at the expense of increased weight and possible corrosion problems if the tungsten wire is exposed.

The long term alternatives to superalloys in jet engines will more likely be Carbon/Carbon (C/C) or other ceramic composites. C/C composites are now in an advanced state of development for low-stress applications in jet engines (e.g.

afterburner components). Advantages include light weight, high wear resistance and high temperature resistance. Disadvantages include surface fatigue cracking and high temperature oxidation. Industrial research is at a stage where jet engine afterburners will be operational in 5 years. High stress applications will be operational in only ten or more years. C/C composite technology is an active industrial research area deserving considerable support.

Indirect cost and performance advantages will be gained by substitution of composites for traditional materials in jet airframe and structural parts. Stealth and cruise missile technology will develop hand in hand with advances in composites technology.

A resurface of interest in composites technology directed towards the automotive industry could occur as broader consumer acceptance, lower production costs and design concepts lead to a general expansion of composite materials markets and lower prices. CAFE regulations have been instrumental in creating an environment leading towards novel conceptualization of automotive designs and materials usage. However, these pressures have been relieved by automobile downsizing to meet CAFE standards in the short-run. New auto body parts production and assembly technologies are more likely to impact the use of composites in automotive industry over the next ten years. The impact of composites technology on critical materials (mostly chromium) will be largely indirect, through weight reduction and performance enhancement. The rate of introduction of composites in substantial quantities is not expected to increase before the 1990's.

In the oil and gas production equipment area, composites have and are expected to see continued use, though at a cautious pace.

Fiberglass tubing for pump rods and inner tube strings have already seen field use. Fiber-reinforced metals are being considered for downhole pump parts and drill bits. Acceptance of composite materials by the oil and gas drilling and production business is expected to be limited until the primary oil companies show a major committment to their widespread introduction.

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1. WHAT IS A COMPOSITE?

In its broadest definition, a composite is any material which is composed of two or more physically distinct material phases. Using this definition, The Handbook of Composites (1) considers filled plastics, fabric laminates, and even wood to be composite materials. For the purposes of this study, this definition is too broad.

For this study, a composite is considered to be any rigid man-made structural material in which a filamentary reinforcement is embedded in a binding matrix yielding a material with physical properties that exceed the properties of its constituents taken alone (within this study, whiskers are taken to be filaments because of their high aspect ratios). This definition excludes filled plastics where the filler is not filamentary (e.g. talc, glass beads, kaolin), flexible film/fabric laminates (e.g. urethane coated nylon), homogeneous materials which separate into two phases during processing (e.g. partially stabilized zirconia, precipitation hardenable steels), and wood.

In composites, as defined above, each constituent serves a unique function. The filaments provide the strength and stiffness while the matrix provides the body of the finished composite product. The strength/structure roles of the constituent materials provide a second, operational definition of a composite.

In addition to strength and stiffness, the filaments enhance other properties of the composite. Often the filaments will increase the maximum service temperature by adding high temperature strength to the composite. Also, certain filaments can enhance thermal stability, attributable to their low coefficients of thermal expansion.

Likewise, the matrix provides more than the body of the composite. In unidirectional composites (all of the filaments aligned in a single direction), the matrix provides most of the transverse (perpendicular to the fiber direction) properties including tensile strength and compressive strength. The matrix also contributes to the shear strength and inter-laminar shear strength of the composite. Additionally, the matrix is responsible for much of the chemical resistance. Finally, the matrix determines the visual and textural appearance of the finished composite product.

In the following sections, commercially available and developmental reinforcements and matrices will be discussed individually. Included in each section is a discussion of the chemical and physical nature of the material, a brief description of its production (including raw materials), the available commercial forms (if applicable), and, for the reinforcements, typical physical properties.

2. TYPES OF REINFORCEMENTS

The following reinforcements are discussed in the order of decreasing current commercial importance: glass, graphite, aramid, boron, and other inorganic fibers (silicon carbide & alumina). Principal properties and costs are compared in Table 1. Other materials which have been used as reinforcements but which are primarily experimental include inorganics (e.g.

Table 1
Comparitive Properties of Selected Reinforcing Filaments

Material	Tensile Str. MPa (ksi)	Tensile Mod. GPa (msi)	Specific Gravity	Approx. Cost ($/lb)	Relative Sp. Strength	Relative Sp. Stiffness
E-Glass	3.45 (500)	72 (10.5)	2.54	.81-1.05	1.00	1.00
S-Glass	4.58 (665)	85 (12)	2.48	4-5	1.36	1.21
High Mod. Graphite	2.07 (300)	689 (100)	1.96	250-1250	.77	12.4
High Str. Graphite	4.28 (620)	289 (42)	1.72	35	1.83	5.93
Low Str. Graphite	2.07 (300)	206 (30)	1.70	15-20	.90	4.27
Aramid (Kevlar 49)	2.76 (400)	124 (18)	1.44	11-44	1.41	3.03
Boron on Tungsten	3.45 (500)	406 (58)	2.48	250	1.02	5.78
Alumina (Fiber FP)	1.38 (200)	377 (55)	3.95	200	.26	3.37
Silicon Carbide	2.42 (350)	179 (26)	3.11	395	.57	2.03
Tungsten Wire	3.77 (550)	345 (50)	19.2	30-70	.14	.63

boron nitride, silicon nitride), metal wires (e.g. tungsten, molybdenum), and polymer filaments (e.g. nylon, polyester).

2.1 Glass

Fiberglass is formed by drawing filaments of glass through a spinneret from a furnace containing molten glass. The resultant glass fibers are used as reinforcements in a variety of forms, including continuous filaments, chopped or milled fibers, woven fabrics, and reinforcing mats. The diameter of the filaments is typically between 0.0001 and 0.001 inches and can be accurately controlled by varying the composition, temperature, or draw rate during production.

To improve the adhesion between the glass fibers and the matrix, several chemical coatings or "sizings" have been developed. The chemical structure of a sizing is such that one end of the molecule bonds strongly with the reinforcement while the other end bonds with the matrix. Specific sizings have been developed for use with epoxies, polyesters, polyimides, and others polymer matrices. The sizing is applied from solution to the filaments after they have been formed.

The principal raw materials for producing glass filaments are silica sand (SiO_2) and limestone ($CaCO_3$). Other minor constituents include boric acid, boron oxide, clay, coal, fluorospar, and lead. These are added to modify the properties of the glass for specific applications. High silica and quartz glass are also produced, consisting of 95% and 99.95% silica sand, respectively. These glass fibers are used in specialty applications in high temperature or highly alkaline environments. They do not constitute a large share of the fiber glass market. (2 Hndbk of Cmp)

Glass fibers are the dominant reinforcement in today's composite markets. This is the result of their low cost (due to cheap raw materials and rapid, continuous production), and their market maturity (fiber glass was developed extensively during World War II). They are used primarily with polymeric matrices. Physical properties of several types of glass fibers are listed in Table 2.

Table 2

Properties of Selected Glass Filaments

Material	Tensile Str.	Tensile Mod.	Attributes	Cost/lb
A-Glass	30.3 (440)	---	Good chemical resistance	$2.00
C-Glass	30.3 (440)	69 (10)	Excellent chemical resistance	$4.50
E-Glass	34.5 (500)	72 (10.5)	Electrical resistance	$1.00
S-Glass	45.8 (665)	85 (12)	High strength	$4.25
M-Glass	---	113 (16.4)	High modulus	---

A-Glass - High alkali (lime, soda) composition
C-Glass - Borosilicate glass
E-Glass - Low alkali composition
S-Glass - Magnesium aluminosilicate glass
M-Glass - Beryllium oxide glass (toxic)

Tensile Strengh - units: MPa (ksi)
Tensile Modulus - units: GPa (msi)

2.2 Graphite

Graphite fibers can be formed from a number of precursors and by a variety of processes. In a typical process, a precursor filament is formed from a polymeric material which contains macromolecules with long carbon "backbones". Precursors include polyacrylonitrile (PAN), pitch, rayon, polyesters, polyamides, polyvinyl alchohol, phenolics, and several others (4 books). Of these, only the first two are now used extensively for commercial production of graphite fibers.

The polymer filaments are first "stablized" in an oxidizing environment at approximately 200°C. They are then carbonized at 1500 °C in an inert atmosphere. This drives off most of the non-carbon atoms from the precursor and results in a carbon filament which is 80-95% carbon (8 Hnd) carbon by weight. The carbon fibers are finally graphitized at temperatures that can exceed 3000°C. During the graphitization stage, the fibers may be externally strained to help induce the preferred crystal structure.

Commercial "graphite" fibers do not, in general, have true graphite crystal structure. Rather, they are "turbostratic" graphite (5), where the layer planes of carbon are slightly displaced from their true graphite orientation. For optimal properties, the basal planes of the carbon atoms should be parallel with the axis of the filament and the planes should align perfectly in the true graphite conformation.

The theoretical maximum for the tensile strength and modulus of a single crystal of graphite is 100 GPa (14.6 msi) and 1000 GPa (146 msi), respectively (9). Commercial graphite is available with either high tensile strength or high modulus, but not both in the same fiber. High strength fibers are available with tensile strength up to 4.27 GPa (620 ksi). Commercial high modulus fibers are marketed with moduli up to 689 GPa (100 msi).

2.3 Aramid

Aramid fibers were inroduced by E.I. duPont under the trademark Kevlar in 1971. Currently, Akzo Inc. of Holland and two Japanese firms are also marketing aramid filaments in addition to duPont (7 Dr. R. Allred). Chemically, aramid fibers are poly-p-phenylene teraphthalamide which is a poly-condensation product of teraphthaloyol chloride and p-phenylene diamine.

Structurally, aramid is a highly crystalline polyamide fiber with at least 85% of the amide linkages attached directly to two aromatic rings (Comp Hndbk). The polyamide macromolecules are oriented along the fiber axis during processing, leading to a fiber with strong covalent bonds in the direction of the fiber axis but with relatively weak hydrogen bonds transverse to the axis. This structure is responsible for aramid's high tensile strength of 3.27 GPa (475 ksi) (9), It is also responsible for aramid's low strength in compression.

Aramid filaments are commercially available in 195, 380, 1420, and 2130 denier sizes (1 denier = the weight in grams of 9000 meters of filament). Individual fibers which make up these filaments are typically 0.47 mil in diameter.

2.4 Boron

Usually, boron filaments are made by chemical vapor deposition of boron trichloride onto an electrically heated tungsten wire or graphite fiber. This process is extremely slow, with production rates per deposition reactor of about two pounds per week. Boron filaments produced by this process are available in 4, 5.6 and 8 mil diameters.

Boron filaments are frequently coated with a barrier coating to prevent chemical attack on the filaments which is particularly acute when the filaments are used in metal matrices. SiC and boron carbide have been used for this purpose.

The tensile strength of commercial boron filaments is 3.45 GPa (500 ksi) (10). The modulus of 4 mil boron on tungsten filaments is 380 GPa (55 msi).

2.5 Silicon Carbide

Silicon Carbide (SiC) filaments are formed by a chemical vapor deposition process similar to the production of boron. SiC production, however, has three advantages. First, production rates are twice those of boron. Second, the chemical which is decomposed is a silane and its market price is significantly lower than that of the boron trichloride used in producing boron filaments. Finally, only 8 lbs of silane are required to produce one pound of SiC fibers as compared to 15 lbs of boron trichloride per pound of boron fibers.

SiC fibers are available in 4, 5.6 and 8 mil diameters (12). They posess the following properties: Tensile strength - 3.45 GPa (500 ksi) Tensile modulus - 448 GPa (58 msi) (13).

An alternative process for forming SiC fibers is under development which entails thermal decomposition of poly(silastyrene) filaments. The process is similar to the production of graphite and may become a more cost effective way of producing SiC fibers.

2.6 Alumina

Alumina fibers are currently produced by E.I. duPont Inc. and are trademarked Fiber FP. This material is a continuous filament polycrystalline alpha alumina yarn. It is marketed principally for high temperature metal matrix applications.

Alumina fibers are produced by extruding an aqueous gel of aluminum hydroxychloride through spinnerets, drying the resultant fibers, and then sintering the fibers at temperatures up to 1300 C. The principal raw materials for the manufacture of these fibers are alumina powder, water, hydrochloric acid, and small quantities of magnesium chloride (used to adjust the viscosity of the gel).

2.7 Others

Other filaments which have been developed in laboratories but which do not currently have commercial significance in composites applications include boron nitride, silicon nitride, high modulus polyethylene, thermotropic polyester, and polyamides.

3. TYPES OF MATRICES

The matrix surrounds the reinforcing filaments and provides structural integrity and transverse (perpendicular to the direction of the filaments) strength. Because of the high aspect ratio of the filaments, they cannot bear compressive loads without buckling unless they are supported by a matrix. You cannot push a rope! Without the matrix, a "composite" would be only a collection of oriented filaments.

Matrices fall in one of the following categories: polymeric, metallic, or ceramic/glass. In addition, carbon has been used as a matrix and it is not clear whether it is best classified as a ceramic or polymer.

Reflecting current commercial importance, matrix materials will be discussed in the following order: polymeric, metallic, carbon, ceramic/glass.

3.1 Polymeric Matrices

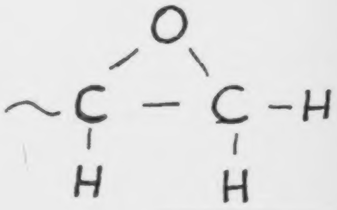
Polymeric matrices can be subdivided into thermosetting and thermoplastic matrices. Of these, the former has greater commercial significance.

3.1.1 Thermosetting Matrices

Thermosetting polymers are made from chemically reactive polymer precursors which, when processed, undergo an irreversible chemical change (polymerization). The prepolymers are usually viscous liquids which transform into solids as the chemical reaction proceeds. Heat and a catalyst or initiator usually must be added to initiate and accelerate the polymerization. Three thermosetting resins, epoxies, polyesters, and polyimides, are discussed in detail herein.

3.1.2 Epoxy Matrices

Epoxies are characterized by the epoxide end groups, a cyclic structure of a $C_2 H_3$ group bound doubly to a single oxygen atom. There are a near infinity of commercially



available variations in the chemical structure between the end groups.

Epoxy prepolymers are normally viscous liquids or pastes at room temperature. They are polymerized into rigid solids by the addition of one of several types of curing agents including amines, amides, anhydrides, and Lewis acids. The Handbook of Composites (13) lists seven epoxy precursors, twelve reactive diluents (used to reduce the viscosity and improve the processability of the resins), and twenty seven curing agents. This is only a fraction of the available materials. Each combination yields slightly different properties and are used for slightly different applications. Alternative formulations affect cured resin properties such as the service temperature, chemical resistance, adhesiveness, processing conditions, flexibility, strength, and pot life.

Epoxy matrices dominate the high performance composites market. Advantages of epoxies include good physical properties, low moisture sensitivity, ease of processing, wide commercial availability, and relatively low cost (typically 2-10 $/lb).

3.1.3 Polyester Matrices

Polyesters are characterized by the ester linkage in the polymerized resins. They are processed in a manner similar to the epoxies and are commecially available in as large a number. The polyester resins most frequently used in composites can be divided into two categories: unsaturated and vinyl.

Polymerization of polyester prepolymers occurs when the prepolymer resins are mixed with free-radical catalysts. Typically, the catalyst is either a peroxide or an azo compound. As with epoxies, a large number of catalysts and formulation modifiers are commercially available. The choice of prepolymer resin, catalyst, and modifier effect the properties and end uses of polyesters.

Polyesters dominate the markets for matrix materials, outselling their nearest competitor (epoxies) by nearly two orders of magnitude. It is the preffered matrix material for high volume markets because of its low cost (typically 0.50-2 $/lb) and generally good physical properties.

3.1.4 Polyimide Matrices

Polyimide matrices are of two types, condensation and addition. Condensation resins consist of a solution of a diamine, a suitable solvent and either a di-anhydride, a tetra-acid, or an ester-acid. These resin solutions are polymerized/imidized by the application of heat. During imidization, they give-off water and other volitiles and these emmissions can cause several problems for polyimide composites including porosity and poor dimensional stability. To circumvent these problems, addition type polyimides were developed. In addition type polyimides the prepolymers are already imidized, eliminating the evolution of volitiles.

Polyimides are highly aromatic/hetrocyclic polymers. This structure is directly responsible for their extreme (by polymer standards) temperature stability. Polyimides have been developed which can maintain physical properties for continuous operation at 700 F.

Polyimides are used only in specialty applications because of their high cost (typically 50 $/lb). They possess the highest heat resistance of any of the polymer matrices and can be cost effective for applications where a premium is placed on weight or where they are used as substitutes for a costly metal.

3.1.5 Other Thermosetting Matrices

In addition to the above mentioned resins, composites have been made from phenolics, furans, melamine-formaldehyde, and others. Each of these resins is specially suited for application in certain environments. Their commercial significance as matrices for filamentary composites is not large.

3.2 Thermoplastic Matrices

Thermoplastics are characterized by their ability to transform reversibly from solids at low temperatures to viscous liquids at elevated temperatures. Generally they have high deformability, relatively low strengths, strengths which decline with increasing temperature and low maximum service temperatures (typically less than 275°F).

There are at least twenty different thermoplastic resins which can be used as matrices for filamentary composites. Some of the more common resins include polyamide, polycarbonate, and thermoplastic polyester. In addition, there are specialty resins which include polyetheretherketone and polyetherimide.

In general, the specialty resins are designed for use at higer temperatures, up to about 400°F. They are usually more costly and more difficult to process and are, therefore, used only in applications where the more common thermoplastics are inadequate.

Most often, a thermoplastic composite consists of a discontinuous reinforcement such as chopped glass or graphite in a thermoplastic resin. Such materials can be processed with conventional molding equipment (injection molding, extrusion, blow molding). Chopped fiber composites attain only a fraction of the physical properties which can be achieved with continuous filament reinforcement. They will not be discussed in depth in this primer.

Processes have been developed for producing continuous filament thermoplastic composites. These will be discussed in subsequent sections.

Polymer matrices dominate the composites market and they are most frequently used with glass, graphite, or aramid filaments. The other three matrices, metal, ceramic/glass, and carbon, were developed following the successful commercialization of polymer based composites.

3.3 Metal Matrices

Metal matrix composites are relatively new structural materials. The most developed metal matrix material is aluminum. Other metals which have been experimented with include lead, titanium, stainless steel, magnesium, copper, nickel, and zinc. Virtually any metal can be reinforced however the gains from doing so are often insignificant when compared with the costs. Usually, a more cost effective solution to attaining improved metal properties is to switch to a higher performance alloy or metal.

Aluminum metal matrix composites have been produced using the 6061, 2024, 1100, 356, and 201 alloys. Aluminum composites are designed to compete with titanium. Reinforcing an aluminum alloy can raise its service temperature by 200°F, permitting its utilization in many applications where it otherwise could not be used.

Usually, the reinforcements used in aluminum composites are boron, alumina, or SiC. However, aluminum composites have been successfully fabricated with most of the previouslly mentioned inorganic fibers. Organic fibers are not used with aluminum or other metal matrices because they cannot withstand the high processing temperatures.

Hot or molten metals also tend to attack or solvate the inorganic reinforcements. For this reason, a number of barrier coatings have been developed to impede this process. These include silicon carbide, boron carbide, boron nitride, tungsten carbide, and tantalum carbide. The barrier coating is chemically deposited on the surface of the filament. Surface coatings are also applied to the filaments to improve the adhesion between matrix and reinforcement.

3.3 Carbon Matrices

Carbon matrix composites are high cost specialty materials used in specialty applications and they are still quite developmental. They are produced by operations similar to those used for manufacturing graphite fibers. A polymer composite, usually a phenolic with a graphite reinforcement, is thermally decomposed, yielding a carbon matrix surrounding graphite fibers.

Further heating partially graphitizes the matrix, adding strength to the composite.

During heating, large quantities of decomposition byproducts are evolved. This leaves the resultant carbon matrix highly porous (approx. 50% by volume of the phenolic "pre-matrix" is volatilized). Multiple impregnation/carbonization steps are employed to increase the density and strength of the matrix. The porous carbon matrix is impregnated with a polymer solution, organic solvent, or organic gas and then reheated to decompose the impregnant into carbon. As many as eight or more impregnations may be required befor the desired properties are achieved.

Carbonization of the polymeric matrix produces a carbon matrix which is essentially isotropic. Unlike the graphite filaments, the carbon matrix is comprised of planes of carbon atoms which are randomly oriented. This provides the composite material with transverse properties and with body.

3.5 Ceramic/Glass Matrices

Ceramic matrix composites are still confined to experimental applications. There are no commercial applications of these materials and it is, therefore, difficult to predict how and when they will develop and for what applications they will be utilized. Currently, glass matrix composites are more developed than their ceramic analogs. (The difference between a glass and a ceramic lies in their microstructure. Glasses are amorphous whereas ceramics are crystalline.)

Most glass compositions (e.g. lead, quartz, borosilicate, and boron oxide) have been reinforced on a laboratory scale. Reinforcing filaments include alumina, silicon carbide, graphite and tungsten wire. The reason for reinforcing glasses is to improve the toughness or impact strength, properties which are normally quite low for unreinforced glasses. Also, if an inorganic or tungsten filament is used, the reinforcement can significantly improve the high temperature strength of glasses.

Ceramic matrices which have been examined experimentally include alumina, zirconia, and silicon carbide. Reinforcements are, again, either inorganic materials or metal wires. Composites of these materials are produced by sintering powders or by dehydrating and sintering slurries. Like glasses, ceramics are reinforced to improve their toughness. They do not, in general, benefit from an improvement in high temperature properties.

One technical problem with ceramic/glass composites is establishing compatability between the reinforcement and the matrix. This problem is being rectified through judicious selection of reinforcement/matrix systems and through the application of barrier coatings to the filaments.

In addition to improving toughness, a "pseudo-composite" system is being developed to decrease the porosity of certain ceramics. In this system, a sintered ceramic is impregnated with a poly(silastyrene) solution. The ceramic is then reheated and the poly(silastyrene) is thermally decomposed to silicon carbide. This results in an interpenetrating silicon carbide network. The porosity of the original ceramic is reduced and substantial reinforcement is gained from the silicon carbide. This system is not considered to be a true composite (as defined for this study) because there is not a filament/matrix relationship between the two materials.

4. COMPOSITE SYSTEMS

Composite systems (combined reinforcement/matrix) have seen spectacular growth over the last forty years. Although considered in the early 1900's, composites experienced their first major growth during World War II. Early applications included radomes, aircraft structures, furniture, and automotive panels where composites were selected for their unique properties, including strength, electrical resistance, and immunity to corrosion.

Modern composites have penetrated numerous markets and have been selected as the preferred material for a number of reasons. Some of the most often cited advantages attributed to composites are high specific properties (specific properties are properties per unit weight), good corrosion and chemical resistance, electrical resistance, design flexibility, and cost effectiveness.

Composites offer the designer the ability to tailor mechnaical properties to meet the requirements of the finished product. The mechanical properties of a composite depend on the type of fiber and matrix, the relative proportions of each, and the direction of fiber orientation (composites are strongest and stiffest in the direction of fiber orientation). By varying these parameters, the strength of a composite can be optimized for the loads encountered during its service.

Interestingly, the advantage of design flexibility has also been cited as an impediment to the utilization of composites. Lack of established design practices as well as insufficient design data have prevented composites from being selected for many potential applications. Additionally, when composites are selected for use, they are often used as direct substitutes for conventional materials without redesign. The performance of composites in such circumstances is often less than optimal. The development of sophisticated computer aided design algorithms has served to greatly reduce the complexity of designing for composite structures.

The cost of the raw materials, especially high performance reinforcements such as boron, graphite, and aramid, is another disadvantage to composites. Prices ranging from \$20/lb to over \$1000/lb are typical for these reinforcements. Clearly, materials priced this high will have a hard time competing with conventional materials such as steel, aluminum, or wood. For this reason, advanced composites (those with specific properties exceeding steel) are selected for applications where their unique properties are highly valued.

The productivity of composite product fabrication is also poor. Processing composites is generally labor intensive and time consuming. While innovative techniques for automated, high-speed processing have been developed, their use is not wide spread and they are usually limited to forming specific types of goods.

Finally, once a composite component is fabricated, it is difficult to assess the integrity of the component without destroying it. X-ray analysis, surface etching, and other techniques for checking the integrity of metal structures do not, in general, work on composites. This drawback to composites is being overcome with the advent of non-destructive tests based on ultrasound and laser holography and with improved design procedures and increased experience in end-uses.

The preceeding sections have focused on the raw materials, both reinforcements and matrices. In this section, composite systems will be discussed. Included in each subsection is discussion of the processing, applications/markets, properties, advantages and disadvantages of each system.

Composites are classified according to the matrix system employed. In order of decreasing commercial importance, polymer, metallic, carbon, and ceramic composites will be addressed.

4.1 Polymer Composites

Polymer composites are by far the most commercially developed of the composite systems. The total U.S. consumption of polymer composites in 1982 approached one million metric tons. Of this, 618,000 tons of polyester/glass was the largest share. Additionally, 106,000 tons of reinforced thermoplastics and 28,000 tons of epoxy resins (equivalent to approx. 90,000 tons of epoxy based composites) were consumed.

Consumption statistics for reinforcing filaments are presented in Table 3. The dominance of fiberglass is apparent.

Table 3

U.S. Consumption of Reinforcements in Composites 1982

Reinforcement	Consumption (metric tons)
Glass	280,000
Aramid	900
Carbon	800
Other	10

Applications of polymer composites are too numerous to list comprehensively. High volume markets include boat hulls, plumbing and bathroom fixtures, and automotive body and trim panels. These structures are usually constructed from the polyester/glass system. This system is selected because of its low raw material costs and because processes have been developed for automated, high-speed production.

Low volume, high technology applications of polymer composites are also numerous. Perhaps the earliest of these was the horizontal stabilizer for the F-14 jet which was constructed from boron/epoxy on an experimental basis in 1968. In 1970, the Grumann Corporation approved this application for limited production.

Since then, air frames, air panels, satellite structures, and sporting goods have been built from advanced composites. In each of these applications, advanced composites were selected for their high specific properties.

The advanced composite systems with the greatest number of applications and with the greatest potential for continued growth appear to be graphite/epoxy and aramid/epoxy. Boron/epoxy was the original advanced composite. However, it is no longer the dominant system due to difficulties in processing the extremely hard and brittle boron fibers, high costs associated with producing the fibers and effective competition from the graphite and aramid systems.

4.1.1 Processing Polymer Composites

Processing polymer composites can be accomplished with a number of technologies. Five of them will be briefly described herein. These are: 1) hand lay-up/vacuum bag/autoclave, 2) spray-up, 3) pultrusion, 4) filament winding, and 5) matched die molding including SMC (sheet molding compound).

The technologies used to fabricate polymer composites have been developed over the last forty years. Because other composite systems (metal, ceramic, carbon) are much newer, their technologies for fabrication are not as highly developed. It can be expected that as they develop, processes similar to those used for polymer composites will be developed.

4.1.2 Hand Lay-up/Vacuum Bag/Autoclave

The hand lay-up/vacuum bag/autoclave process, or a derivation of it, is used to fabricate most of the high performance composites used in aerospace. It is highly labor intensive and quite slow and is therefore used for low volume, high value added, high technology finished goods.

As the name implies, hand lay-up/vacuum bag/autoclave is a series of three operations. These operations are not always used together and one or more of them may be an operation within one of the other listed technologies. They are described as a single technology because they represent a series of steps which are frequently used to fabricate finished goods.

The first step, hand lay-up, entails manually forming broadgoods, usually woven reinforcement, to the contours of a mold. The reinforcement is either applied "wet", i.e. saturated with viscous polymer resin, or it may be applied as a "prepreg", reinforcement which is pre-impregnated with a drier resin. In either case, the resin is pre-catalyzed and curing occurs with the application of heat. Typically, molds are made from wood, rigid foam (e.g. polyurethane), hard rubber, fiberglass, or metal.

If porosity and low strength are not critical in the finished good, often the hand lay-up operation is sufficient by itself. The resin is cured as is and, once cured the semi-finished good is removed from the mold. It may now proceed to trimming, painting, or other secondary operaions.

If porosity and strength are required, the lay-up may be vacuum bagged. Vacuum bagging entails first covering the lay-up with a layer of peel-ply and a layer of bleeder cloth. These layers are applied over the last layer of reinforcement. They serve to texture the surface of the composite and to allow gas to escape more readily during evacuation.

Next, the bleeder cloth is covered with a thin film of plyable material. Typically, these films are made from silicone rubber, polyvinyl alcohol, polyamide, or polyimide materials. The film is sealed around the lay-up so as to completely enclose it.

Through a small opening in this "bag", a tube is passed. The tube is connected to a vacuum pump and as the vacuum is drawn, the bag collapses on the lay-up, compacting and densifying it. The resin is cured in this configuration and the semi-finished good is debagged and demolded.

Autoclaving is a technique for applying additional compaction to the lay-up. The vacuum bagged lay-up is placed within an autoclave (essentially, an autoclave is a pressurized oven) and external pressure is applied. This serves to further densify the lay-up, eliminating porosity and increasing strength.

Vacuum bagging and autoclaving are also used in conjuction with filament winding and automatic tape laying. The process is identical except for the method of forming the "lay-up" or preform.

A variation of hand lay-up which is undergoing considerable development is automatic tape lay-up. Tape dispensing machines lay strips of preimpregnated reinforcement tape over a mold. The tapes are availble in a variety of widths. State of the art tape laying machines have five axes of free motion and can be used to lay-up highly intricate structures. These machines are being developed for high technology, low volume, areospace applications including aircraft panels. Generally, the tape consists of a graphite or aramid reinforcement in an epoxy matrix.

4.1.3 Spray-up

Spray-up is the technology used to fabricate boat hulls and other goods where specific strength is not critical. Spray-up is not highly labor intensive and, compared with other processes, it is relatively rapid. For these reasons, it commands a substantial portion of the high volume composites markets.

In spray up, an open mold is created which has the desired shape of the finished good. The mold is coated with a releasing agent such as wax, silicone, or Teflon. Next, the mold is sprayed with a thin gel coat of resin. The gel coat serves to keep the reinforcement (invariably glass) from penetrating the outer, finished surface.

The gel coat is sprayed alternately with chopped fibers (up to 3 in. long) and with a polymer resin, usually polyester. In most modern equipment, the resin and glass can be sprayed simultaneously. The chopped fiber reinforcement in a sprayed-up structure is usually randomly oriented. When the desired thickness of resin/glass mixture has been applied, the mold is transfered to a curing station.

Variations of the spray-up process have been developed which control the orientation of the reinforcing fibers. This permits maximization of strength in the desired directions. Other spray-up processes incorporate continuous filament woven fabrics. These fabrics are placed directly on the gel coat or they are incorporated between layers of sprayed-up material. Incorporating woven fabrics is another method for increasing the strength of the finished good.

4.1.4 Pultrusion

Pultrusion is a relatively new process for fabricating composites. It offers the advantages of continuous processing and minimal labor requirements. It is not used extensively but does offer considerable promise as a technology for forming composite I-beams, channels, box beams, hollow columns, and other profiles.

Pultrusion is a continuous process that can be analyzed as a sequence of six distinct operations: filament dispensing, resin wet-out, excess resin removal, die forming or shaping, gripping/pulling, and part cut-off. The process is similar to the extrusion of metal or plastic profiles in many respects.

In pultrusion, continuous reinforcing filaments are pulled from dispensing creels through a bath which coats the filaments with a thin film of thermosetting resin. The filaments are pulled through progressively smaller shaping dies to remove the excess resin. The final die forms the wetted filaments into the shape of the desired profile. The die contains banks of imbedded heaters and as the coated filaments are pulled through it, heat causes the resin to polymerize and harden. The cured profile is pulled from the forming die and cut into the appropriate lengths.

Pultrusion is used to process epoxy and polyester thermosetting resins. The filaments are standardly glass, aramid, or graphite. Pultrusion is usually used to fabricate components which have constant and uniform cross-sections, however, dies have been developed which vary the cross-section of the profile as it is formed.

4.1.5 Filament Winding

Filament winding is also a relatively new technology for fabricating composites. It is not highly labor intensive and can be fairly rapid. For these reasons, it is expected that filament winding will be used extensively for fabricating composite drive shafts, storage tanks, pressure vessels, and other hollow components.

Filament winding is a cyclic process which may be analyzed as a sequence of four operations. First, filaments are drawn through a resin bath and coated with a thin film of thermosetting resin. (Alternately, the filaments may be pre-impregnated.) The coated filaments are wound around a forming mandrel, similar to the way thread is wound on a spool. Generally, the filaments are wound as bundles or as tapes to expedite the wrapping procedure. When the desired thickness of filaments have been wound onto the mandrel, the assembly is transferred to an oven for curing. Finally, after the resin has cured, the forming mandrel may be removed leaving only the cured outer wrapping or it may remain as an integral part of the finished structure.

Filament winding is used to process epoxy, polyester, or polyimide thermosetting resins and the filaments are generally glass, graphite or aramid. Filament winding can be used to produce components with hollow geometries such as box beams, columns, vessels, or storage tanks.

4.1.6 Matched Die (Including SMC) Molding

Composite products are molded with the matched die technology in a large number of high volume applications. This technology is neither labor intensive nor time consuming. It is used extensively in the automotive and sporting goods markets for the production of items such as fenders and tennis rackets.

A matched die consists of two or more mold sections which have been carfully hollowed. When the sections are brought together, the hollowed regions form a cavity which has the shape of the desired product. A finished good is formed by transferring resin and reinforcement into the cavity and closing the mold under pressure. The resin/reinforcement solidifies in the shape of the cavity.

There are a number of techniques for transfering the resin and reinforcement into the cavity. One of the most common, is to inject them, using short staple fibers (up to 2 in.) as the reinforcement. In other variations, woven or mat reinforcement is first placed in the cavity and the resin is injected around it.

In SMC molding, a sheet of material containing resin, reinforcement, and catalyst is placed between the halves of a split mold and the halves are pressed together causing the sheet to assume the shape of the mold cavity. The mold halves are kept hot, causing the resin to polymerize and harden in the desired shape. When sufficiently polymerized, the finished piece is removed from the mold and forwarded to secondary processing.

By convention, SMC molding implies a glass reinforced polyester resin. This restriction is arbitrary since the process could be used with other materials. Normally, the glass fibers are chopped to lengths of 1/2 to 2 in. and are oriented randomly within the polyester matrix sheet. Variations on the SMC process, HMC and XMC, involve oriented chopped fibers and continuous filaments, respectively.

Split mold techniques can be used to form items with virtually any shape or size. SMC molding is slightly more restrictive and is used to fabricate components with relatively thin walls and uniform wall thicknesses.

4.2.1 Processing Thermoplastic Composites

Thermoplastic composites are processed by similar technologies to those which have been described for thermosets. The principal difference is that heat is used to melt the resin and when the heat is removed, the resin solidifies. The most common form of thermoplastic composite is a mixture of a resin and chopped glass fibers. Such materials can be processed on conventional injection molding, extrusion, etc. equipment. The resultant composite material possesses only a fraction of the physical properties that a similar continuous filament composite would have. Nevertheless, they do provide considerable improvement over non-reinforced thermoplastics.

Continuous filament thermoplastic tapes have been developed for use in modified pultrusion, filament winding, hand lay-up, and automatic tape lay-up operations. Tapes are produced by drawing filaments through a bath of molten resin. Glass, graphite, and aramid filament/thermoplastic matrix tapes have been produced. Virtually any resin can be used as the matrix material.

One advantage to thermoplastic composites is that they can be reshaped when required. This becomes desirable when the composite structure is subjected to potential damage. On the spot repairs can often be performed by heating and refusing an existant thermoplastic structure or by thermally bonding a patch over the damaged area.

4.2.2 Properties of Polymeric Composites

The number and variety of polymer composites which are commercially available precludes a comprehensive tabulation of physical properties. The properties of some of the more common and some of the more exotic polymer composites appear in Table 4. For comparison, the properties of a steel and an aluminum alloy are included.

4.3 Metal Matrix Composites

Metal matrix composites have experienced significant commercial development over the last ten years. Admittedly, they are still primarily laboratory materials. However, a number of sucessful applications exist. Toyota Motor Co. has developed an aluminum/alumina composite for reinforcing the piston ring groove in production diesel engines. They have also been working to develop composite pistons and cylinder heads. In such applications, improved performance is highly valued and this has been the justification for developing metal matrix composites.

There are three principal reasons for developing metal composites. The first is to increase the strength or specific strength of a metal. For this reason, composites have been in development for copper and lead. Copper composites are being considered for applications in electrical power transmission. Strengthening copper would make it possible to use less copper in transmission lines. Lead is reinforced for use in batteries since in certain applications, lead lacks the strength to support its own weight.

The second reason for using metal composites is to increase the maximum service temperature of the matrix material.

Aluminum/graphite and aluminum/boron composites have been developed for use at 525°F. This represents an improvement of 200 °F over unreinforced alloys. High temperature strength makes it is possible to use aluminum composites in applications where titanium (a more expensive metal) is now used.

Refractory metal reinforced superalloys are being developed for use in extremely hot (2800°F) environments. Applications would include jet turbine and rocket components. The refractory metals with the highest potential for use as reinforcement are tungsten and molybdenum. Nickel, cobalt, and iron based superalloys are all being considered for use as matrices.

The third reason that metal matrix composites are being developed is for improved wear resistance. It has been found that ceramic reinforcement, usually as chopped fibers, can significantly improve the wear resistance of certain metals. Aluminum and magnesium are the primary candidates since the wear resistance of these metals is poor. Improved wear resistance (as well as increased high temperature strength) was the primary reason for using a metal composite in the previously mentioned diesel piston application.

One of the major advantages of metal composites over polymer composite systems is that there is not as large a difference between transvere and longitudinal strength. Transverse strength in metal composites is essentially equal to the strength of the matrix metal. An additional advantage which can be important is that metal matrix composites are electrically conductive.

Generally, the cost of metal composites is on the order of ten times the cost of the matrix metal alone. Much of this differential is due to the high raw material cost of the reinforcement. Also, processing complexities add significantly to the total cost. For this reason, metal matrix composites are only considered for applications where the value of their added performance is large.

4.3.1 Processing Metal Matrix Composites

Processing technologies for fabricating metal matrix composites can be divided into two categories, solid phase processes and liquid phase processes. Each process has advantages and disadvantages. Most likely they will both be developed for use with specific composite systems and for specific applications.

Solid phase processing involves diffusion bonding the metal matrix around the reinforcement. The matrix material may start as powder, foil, or sheet. The reinforcement is carefully positioned between layers of sheet or plate or it is imbedded in a loose powder matrix. Either hot or cold pressing are used to consolidate and densify the composite. In one promissing variation of solid phase processing, powder and wires are first processed into tapes which are subsequently cut to length and hot pressed into a laminate. This process is attractive because it permits precise alignment of the reinforcement within the composite.

Liquid phase processing involves casting molten metal around the reinforcement. The reinforcement is prepostioned within a closed mold and maintaining the orientation of the reinforcement within the mold is one of the major technical difficulties encountered in this type of processing. It has been found that large (30 mil) wires maintain their orientation better. Once the reinforcement is positoned, molten metal is poured, injected, or vacuum drawn into the mold.

Liquid phase processing has a major technical disadvantage. Molten metal tends to attack and disolve the reinforcement. While this can also be a problem in solid phase processing (and in the end-use), it is greatly aggrevated by the higher temperatures encountered when working with molten metals. The most successful counter measure to this problem is the judicious selection of matrix/reinforcement alloys to minimize interactions. Also, minimizing processing times is beneficial. Barrier coatings have been applied to the reinforcement in an effort to limit interactions, however, they have not been highly successful, to date.

4.4 Carbon/Carbon Composites

Carbon/carbon composites were born of the need for a thermal shock and erosion resistant material for use on re-entry vehicle nose tips and rocket nozzle throat liners. Carbon/carbon is seen as a replacement for weaker monolithic graphite and expensive specialty metals in these applications. To date, the only commercial application of these composites is as brake liners for aircraft.

Carbon/carbon composites posess a number of highly desirable properties. First, they have demonstrated mechanical integrity at temperatures exceeding 4000°F. Second, the specific gravity of these materials is 1.65, permitting substantial weight reduction when used as a substitute for high temperture metals. Also, their wear resistance is excellant.

There are three major problems which must be addressed before carbon/carbon composites become more commonplace. First, in an air environment, oxidation can severly attack these materials. To minimize this attack, carbon composites which include oxidation inhibiting materials, usually organometallics, zirconia salts or silicates, are being developed. Oxidation is not a problem for space applications. However, it is a major impediment to high temperature air applications of these materials. Potential air applications include a number of low stress jet engine components.

Low interlaminar strength is another disadvantage of carbon/carbon composites. To overcome this problem, special three dimensional weaves of graphite fibers have been developed. Three dimensional weaving is used to produce a "block" of graphite fibers in which fibers are oriented along all three of the major orthogonal axes. The woven block is processed identically to woven graphite fabrics (two dimensional). A component can be machined from this block. With graphite fibers oriented in three orthogonal directions, the problems of low interlaminar strength are eliminated.

Finally, the cost of carbon composites is extremely high. This is the result of the complex weaving procedures, long processing times and high energy consumption during processing. As with most developing materials, the cost can be expected to drop as the technology emerges.

4.5 Ceramic/Glass Composites

Ceramic and glass composites are being developed but are not yet commecially available. They are being developed for structural applications in extreme high temperatures and where high wear resistance is essential.

The primary reason for reinforcing ceramics and glasses is to improve the toughness of these materials. They are notoriously brittle and catastrophic failures can occur when they are used in high stress structural applications. By introducing a reinforcement, the fracture mechanics of ceramic based materials are benificially altered.

Currently, glass matrices appear more promising than refractory ceramic matrices. Composites based on silicate glasses reinforced with 50% (vol.) graphite or silicon carbide fibers have been developed in laboratories. These materials demonstrate fracture toughness approaching metals and maintain physical properties at temperatures approaching 2000°F. Systems based on refractory ceramic matrices (SiC, alumina, zirconia, boron nitride, & silicon nitride) are not as well developed but they are being actively pursued since they offer the potential for application at temperatures exceeding 3000°F.

II. JET AIRCRAFT APPLICATIONS

1. INTRODUCTION

Structural composites are entering a period of explosive growth: 25-30% per year compounded growth rates are anticipated through the 80's. This progression is driven in the transportation industries by the desire to increase performance by substitution of composite materials for traditional materials and to substitute lightweight materials for heavier traditional ones. Replacing metals by composite materials provides two routes to reduce the demand for critical materials.

1) direct substitution
2) Secondary cascading when a component with or without critical materials is downsized.

It is in the aerospace industry that most of this growth in composite materials demand will occur in the short and medium term. Over the next ten years, the aerospace industry could represent over 50% of the total high performance composites market. Significant growth in the automobile/industrial sector is not projected to occur until the late 80's (largely due to cost effects).

Carbon, silicon, carbide and boron fiber composites are among the fastest growing segments of the advanced engineering composites industry, due to their increasing acceptance by and the standardization of product quality for, the aerospace industry.

Most developing aircraft applications of composite materials do not require high temperature performance and can be satisfied by organic matrix composites. However, the use of critical materials in engines is decreased principally by cascade effects associated with downsizing the overall structure, including the engine. Nonetheless, extensive efforts are being devoted to develop composites for high temperature applications. These composites can directly substitute for critical metal structures and alleviate the pressure on available volumes.

Weight reduction in aircrafts translates into fuel savings lower operating costs, increased profits for commercial aircraft, increased range and maneuverability for military aircraft as well as reductions in manufacturing through parts consolidation in both cases. It is anticipated that substitution for metals will reach an average of 50% by the early 1990's. One can see the impetus for substitution of composite materials for critical end-use by market forces alone. Constant economic pressure can be expected to stimulate materials innovation.

The main focus of this section will be the potential for direct substitution of composite materials for superalloys in jet engine application (excluding the downsizing issue).

1.1 Cobalt in Jet Engines : Introductory Remarks

Described in this section will be the use of cobalt in superalloys for jet engines. Yet at the same time, we must keep in mind that geopolitical considerations are very important and have to be incorporated in the decision-making process involving the choice of a new material. This choice is usually made according to the prevailing circumstances, whereas production and use of the material is for the long term and whereas the price trend is not known. It is of utmost importance for the industry and government to avoid short-sightedness and to aggregate political information to economic and technical data. (Fig. AO)

It takes about ten years for an engine program to be completed from design to production and seven years for a new alloy or other material to be introduced due to extensive testing and certification (a fact many composites manufacturers may not realize) . (Figure AO). Adaptation to the market is therefore very slow. That is the reason why, when prices of cobalt went up to six times their previous level, it took some time before some easily replaceable parts were changed in order to consume less cobalt.

In addition, there is a problem of allocation of resources among the various industries, because disruptions may be due not only to high prices, but also (and perhaps with more wide-ranging effects) to lack of availability.

	EVALUATION & PRELIMINARY DEVELOPMENT ◄── 2-3 YRS ──►	SCALE UP & DEMONSTRATION ◄── 3-5 YRS ──►	FULL-SCALE DEVELOPMENT ◄── 4-7 YRS ──►	◄── PRODUCTION
LABORATORY TESTING	ESTABLISH PROGRAM GOALS. SELECT CHEMISTRY. INVESTIGATE FIBER LAYUP FOR COMPOSITES. OBTAIN PRELIMINARY PROPERTIES.	OBTAIN PROPERTIES REQUIRED FOR DESIGN: TENSILE, CREEP/RUPTURE, LOW CYCLE FATIGUE NOTCH SENSITIVITY, CRACK PROPAGATION, AGING, COATINGS, ETC.	COMPLETE CHARACTERIZATION OF MATERIAL. OBTAIN STATISTICAL DATA ON PROPERTIES.	
ENGINE DESIGN	ENGINE CONCEPTUAL DESIGN TEST RIG OR DEMONSTRATOR DESIGN	DESIGN PRODUCTION ENGINE CONFIGURATION		
RIG & ENGINE TESTING	FABRICATE RIG OR ENGINE PARTS	RIG OR DEMONSTRATION ENGINE TESTING INITIAL SERVICE APPLICATION	TEST PRODUCTION ENGINE QUALIFY ENGINE	
MANUFACTURING & QUALITY ASSURANCE	REVIEW MANUFACTURING PROCESS, PRODUCIBILITY, & POTENTIAL INDUSTRIAL BASE.	EVALUATE MANUFACTURING SOURCES. DEVELOP QUALITY ASSURANCE METHODS. ASSESS PRODUCTION COSTS. DEVELOP VENDOR CAPABILITY.	CHOOSE MANUFACTURING METHODS & VENDORS. INVEST IN FACILITIES & TOOLS. ESTABLISH QUALITY ASSURANCE SYSTEM.	
FUNDING	6.1, 6.2, IR&D	6.2, 6.3, 7.8, IR&D, INDUSTRY	6.4, 7.8, INDUSTRY	

6-3-82-10

FIGURE AO Typical high-temperature material/engine program. (35)

In such a case, the aerospace industry seems to have the highest priority because, as we pointed out, substitutions are difficult, costly, and above all, long to implement. Price is not a real problem for jet engine manufacturers. For example, in a Pratt & Whitney JT-9D engine (used in the Boeing B-747), 900 pounds of cobalt are used, which amount to around $10,000 to be compared to $2,000,000 for the cost of the engine.(1) Consuming 100 pounds more or less in an engine is thus marginally important as far as the price is concerned. But if cobalt were to become unavailable, jet engines manufacturers would have some trouble in replacing it in the short-term, the whole engine having to be redesigned in order to use alternative materials.

Up to now, the main strategy has been to replace cobalt-base alloys with nickel-base alloys containing some cobalt. The objective was to reduce the percentage from 90% (in some alloys) to 20%. Now, the objective is reduction from 20 to 10%. Jet engines manufacturers have indeed come to realize that they could get the same properties while drastically reducing the amount of cobalt. The case of Pratt & Whitney is particularly dramatic, as they used high percentagesof cobalt because they found cobalt-based alloy parts easier to repair and much more corrosion-resistant than nickel-based alloy parts. Pratt & Whitney, after extensive research, even uses cobalt-free alloy nowadays.(1)

The current reduction in the price of cobalt (especially compared to nickel prices) has not stopped the substitution process, because, as we pointed out earlier, the problem is more availability than price. Moreover, research is going on and improvements in performances are being made with smaller amounts of cobalt. One of the greatest moves has been from wrought alloys to cast alloys which use less cobalt. The beneficial effect of the 1978 crisis was thus to make people aware of the high concentration of the cobalt supply market (very few producers supplying most of the cobalt in the world) and all the consequences this may have.

1.2 Jet Engines: General Description

The design requirements of aircraft jet engines require the ability to handle high air mass flows, high temperature and large, though light, compressors. Improved high pressure turbine blade cooling technologies are necessary for the increasingly high inlet temperatures required in jet engines. This leads to the need for more advanced materials in the compression and turbine zone of the engine. In addition, these materials must be sufficiently robust, reliable and cheap to remain technically(3) and economically competitive.

The basic gas turbine engine is shown in Figure A1, which gives the schematic diagram of a turbojet. It consists of 1) a diffuser, where the incoming air is slowed down, and its temperature and pressure are thus increased; 2) a compressor, which raises the pressure and the temperature in order to improve the efficiency of the engine; 3) a burner, or combustor, in which fuel is mixed with air and burned; 4) a turbine, where vanes direct the hot combustion gases against the turbine blades which drives the compressor and in which the temperature decreases, 5) a nozzle, where the gas flow is expanded, thus decreasing the pressure and the temperature. The gain in kinetic energy in the nozzle is higher than the loss in the diffuser, thus providing the thrust.

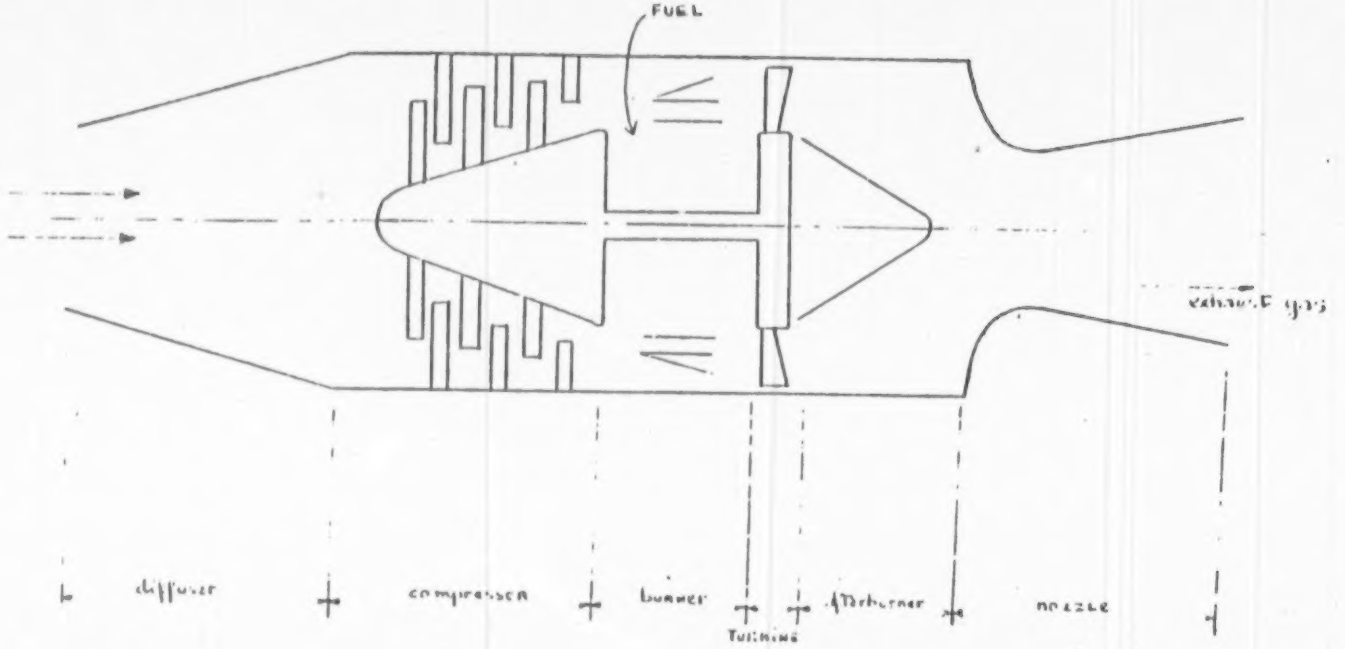

FUEL
exhaust gas
diffuser
compressor
burner
turbine
afterburner
nozzle

Figure A1. Schematic Diagram of a Turbojet

An afterburner may be added in order to increase the available thrust in brief pulses by burning the remaining gases mixed with some additional fuel. Afterburners are used mainly in supersonic aircrafts, because they have a very poor fuel efficiency at subsonic speeds. Turbojets have been widely used, but most modern engines are turbofans in which a by-pass is added. A fan pumps air through the by-pass. This fan is either driven by the compressor turbine (single-spool engine) or by the fan turbine, named fan turbine, located behind the compressor turbine and running at a lower speed (3,000 to 4,000 rpm). The latter type is the most frequent and is named twin-spool engine. It is shown in Figure A2. In twin-spool engines, the front part of the compressor, named the low-pressure section, is driven by the fan, and the rear part, or high-pressure section, is driven by the compressor turbine and runs at higher speed.

Turbofans are characterized by the by-pass ratio, which is the ratio of the secondary air flow to the primary air flow. The by-pass increases the fuel efficiency at subsonic speeds; the ratio is 5:1 for civil subsonic aircrafts. However, for military supersonic aircrafts, a trade-off has to be made between good performance and fuel efficiency, and a typical by-pass ratio is 0.55:1.

The compressor in a turbofan consists of about fourteen stages (for example for the engines equipping

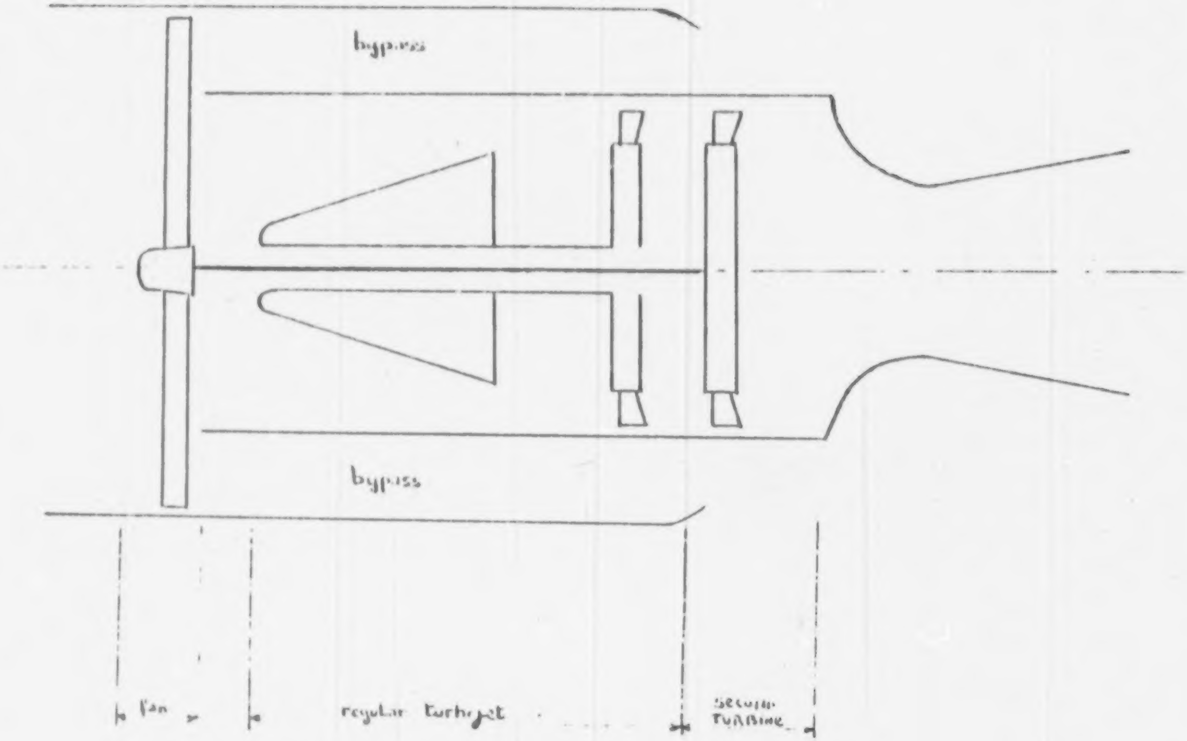

bypass
bypass
fan
regular turbojet
second turbine

Figure 2 Schematic Diagram of a Turbofan

Airbus), 3 to 5 in the low-pressure section, the remaining in the high-pressure section. A stage consists of a set of blades attached to the periphery of a disc (rotor blades), followed by a set of vanes or stator blades, which are fixed.

A turbine consists of 5 to 7 stages, 1 or 2 for the high-pressure section (compressor turbine), and 4 to 5 for the low-pressure section. In turbines, contrary to compressors, blades follow vanes. The most critical vane is the first one; a thermal barrier coating of Yttrium-stabilized Zirconia is for example used by Pratt & Whitney. This coating does not conduct the heat on the platforms fixing the vane. But this type of coating cannot be used on blades.

The pressure on blades reaches 100,000 psi, temperature 2,750oF, and a disc rotates at 30,000 rpm or more. The material used must therefore be particularly creep-resistant. Blades and disks thus experience high temperature, and extreme stress and corrosion conditions. Vanes generally operate in a high temperature though lower stress environment.

1.3 Use of Cobalt in Jet Engines

Cobalt is of utmost importance in jet engines today. In 1978, Pratt & Whitney used three million pounds of cobalt out of 18 million for total U.S. consumption.(4) The United States' share of the world's consumption of superalloys is 50%, with 75% of these for aircraft applications.

In a modern jet engine, the "front" section (fan, two-thirds of the compressor, the outer cases and half nozzle) is made principally from titanium. The "rear" section (one-third of the compressor, combustor, turbine, afterburner and half nozzle) is constructed from superalloys. As we said, the parts most critical for engine performance are in the hottest "rear section. Cobalt is used for blades and discs in these areas because of its thermo-mechanical properties. Originally, cobalt was selected for its good forgeability. Now, its most appreciated property is its high-temperature strength. For example, about 110 lbs of cobalt (plus 110 lbs of scrap, which gives an amount of 220 lbs of raw metal) is used as nickel-base superalloys in each Rolls-Royce RB-211 engine(5) (installed on Tri-Star and Boeing B-747 and planned for Airbus A300-B10 and YX, a Japanes project. Other examples are given in Table A3 (sources: Deutsche Lufthansa for civil engines, Pratt & Whitney for military engines). Cobalt use is computed on the basis of a material requirement for manufacturing

Engine	Weight in tonnes	Aircrafts equipped	Cobalt Alloy in kgs	Cobalt Content in kgs	Cobalt Alloy Content in % of weight	Cobalt use in kgs
Rolls-Royce RB-211		Tri-Star, Boeing B-747, Airbus A 300-B10 (in development), YX (project)	100	50		80
Pratt & Whitney JT3D-3B	1.97	Boeing B707-320	135	60	6.8	96
Pratt & Whitney JT-8D	1.48	Boeing B 727, B-737, Douglas DC9	78	17	5.3	27
Pratt & Whitney F-100		Military engine for F-15 and F-16				70

Table A3 Cobalt use in typical jet engines(3)

60% higher than the actual use, due to high processing losses. The low cobalt content of the JT8-D is due to the use of Inconel 718 (cobalt-free) instead of Waspaloy in turbine discs. The increase in the weight of the engine due to this change is small: only 10 lbs. In the Pratt & Whitney F-100 engine, the 150 lbs of cobalt come from 870 lbs of raw metal; that gives a "buy-fly" ratio of 6:1.

Research has been done, especially since the 1978 cobalt supply disruption, for saving cobalt in jet engines. There are several alternatives:

- Substitution:
    - direct in engines: this is not easy.
    - new alloys: it takes more than 7 years to develop a new alloy (laboratory testing and characterization, rig test, ground engine test, flight test).
- Processes Improvement:
    - manufacturing techniques can be improved in order to obtain directly "near-net-shape" parts to minimize scrap losses.
- Scrap Recovery:
    - by buying old parts back from airlines which are replacing them.
    - by using scrap due to tooling. For example, Pratt & Whitney recovers 65% of the scrap

> coming from Inconel 100: the scrap is "degreased", remaining carbides due to the tooling are removed then melted. Metallurgical and motor tests have proved that the alloy thus recovered by this process is as good as the original one. However, recovery is not economical, because there is no immediate pressure. But in case of a disruption, it would be an interesting alternative.

At Pratt & Whitney, the goal for 1990 is 425 lbs of cobalt per engine, which is 50% less than the current use. Means for accomplishing this include the Rapid Solidification process, use of composites, improvements in design with less parts (4 or even 5 stages instead of 10).(6)

Another tendency would be to reduce the use of cobalt in superalloys rather than to eliminate it. A first step is the reduction in use of cobalt-base alloys and replacement with nickel-base alloys. For example, in combustion chambers, cobalt-base alloys may be replaced by nickel-base alloys with a refractory coating acting as a thermal barrier, and with cooling in order to reduce the temperature to which the alloy is exposed. Also, vanes are made of single-crystal nickel-base alloys, which are more expensive but do not contain cobalt.

A second step is the reduction in percentages of cobalt in nickel-base alloys for blades and discs. There are already some discs without any cobalt, but not for the hottest areas. However, attention must be paid to the fact that replacement of cobalt alloys with alloys containing other critical materials (critical meaning here that their market is also likely to be disrupted) is not a wise solution to the problem.

A third step involves single-crystals and Directed Solidification.

The main advantage of cobalt-bearing alloys is that the creep resistance does not collapse at high temperatures. It corresponds to Graph #2 on Figure A4 (Graph #1 represents a material with higher creep and Graph #3 a material with lower ductility). Creep resistance is particularly important in turbine blades and discs because of high rotation speeds leading to high centrifugal stresses. But also important is their resistance to corrosion in hot environments. Substitution of cobalt with nickel may have some influence on the resistance to wear and tear, and blades may have to be replaced more often.

Elimination of cobalt in the hottest areas of an engine seems to be difficult, except if totally new materials, such as composites and ceramics, are developed.

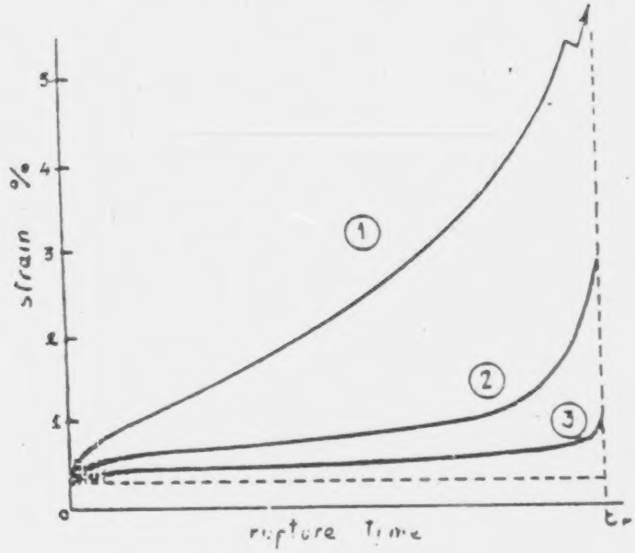


Figure A4 - Typical creep resistance behaviors

1.4 Effect of the Choice of an Alloy on the Performance of an Engine.

We pointed out in the previous chapters that extensive research is being done to consume less critical materials such as cobalt in temperature-resistant alloys. In the long run, many solutions will become available: new processes, ceramics, and supply from seabed mining. But even if, in the short run, jet engines manufacturers are able to lower their consumption of cobalt, they are not able to suppress cobalt completely from engines within a short time. If a severe disruption occurs, they will not be able to build engines with the same performances. Criteria regarding these performances are efficiency, weight, durability and cost. Reduction of cobalt would lead to a loss in at least one of these performances. We will see below what the consequences of using an alloy which is less temperature-resistant than current cobalt-bearing alloys might be.

The reason for doing research on superalloys and for trying to increase their temperature resistance is to increase the turbine inlet temperature in order to obtain better efficiency. Conversely, if we have to reduce the turbine inlet temperature because of a less temperature-resistant alloy, efficiency and thrust will decrease, and penalties in terms of weight, and therefore in terms of payload, will occur. We will compute these losses and do some cost-benefit analysis in order to know how much a company is willing to pay more for purchasing engines with the previous performances (viz, without the losses).

As we have seen, some of these substitutions have already begun. Some are easy. For example, combustors, currently made of HA-188 (with 45% cobalt) may be covered with ceramics (because they are not highly stressed) and thus allow the use of cheaper cobalt-free alloys as a base. But substitutions are much more difficult in blades and vanes, and actual cobalt-free substitutes are still not available.

1.5 Materials for Jet Engines

An essential feature underlying future development of jet engines will be to provide materials with improved strength to weight ratios, strength properties at higher temperatures and fatigue corrosion and impact resistance, which at the same time satisfying economic/cost and reliability criteria. Physical properties and characteristics necessary for jet engine materials (Fig. A. 5) are closely associated with individual components in each section of the engine. (1,3,5)

1.5.1 Compressor Stage

At the compressor stage of a jet engine, the rotating parts are the most highly loaded. These include the discs, blades, shafts and bearings. Compressor temperatures range from -50° C at inlet to 500^{0} C at outlet. Materials chosen for this section of the engine must satisfy tensile, stiffness, fatigue, creep, and adequate corrosion, erosion and impact resistance constraints. In the hottest stages, nickel-based superalloys are required. Also some 14% Cr martensitic steels have been used.

A more detailed description of superalloy use in specific engine parts will follow: Turbine Blades, Discs and Nozzle Guide Vanes.

1.5.2 Turbine Blades

Turbine blade materials must satisfy both the high-stress/low-temperature requirements of the blade root and the low-stress/high-temperature requirements of the blade tips, passing through the high-stress/high-temperature critical zone around mid-blade. (Stresses range typically from 120 to 200 MN/m^2) In high temperature regions of the engine, turbine blades have typically been made of nickel-based superalloys.

Under medium-level stress and temperature conditions, addition of Ti and C have the effect of adding creep resistance. For high rotational speed and high temperature applications, a nickel-titanium-aluminum compound is distributed in the oxidation-resistant nickel-chromium matrix. Addition of cobalt serves to improve workability. (Molybdenum can be used to substitute to a certain degree for a fraction of the cobalt). Cobalt controls the structure

Distribution of Metallic Materials in Aero Gas Turbines, wt-%

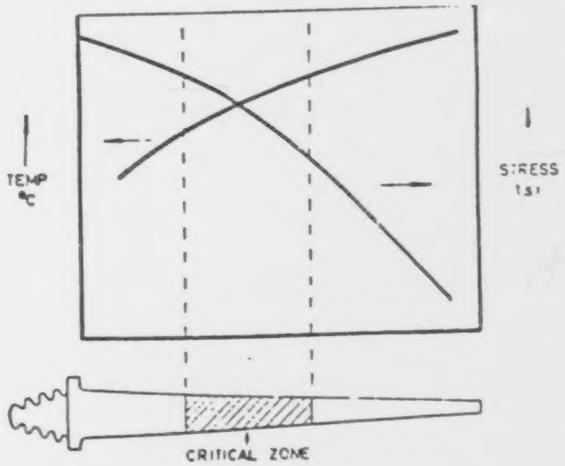
Material	GE J47 (c. 1945)	RR Avon (c. 1955)	RR Spey (c. 1960)	Typical USA engines (c. 1972)	RR RB 211 (c. 1969)	GE TF 39 (c. 1965)
Al and Mg alloys	22	~20*	~12*	2-4	~9*	3
Steels	70	~60	~60	15	~46	19
Titanium alloys	0	0	~ 4	* 18-25	~20	29
Ni and Co superalloys	8	~ 8	~11	55-60	~21	47

* Al alloys only
RR engines; Ref. 72
GE and USA engines; Ref. 34

Melting Points and Densities of Base Metals

Metal	Melting point, °C	Density, 10^3 kg m^{-3}
Magnesium	650	1·74
Aluminium	660	2·70
Titanium	1668	4·5
Beryllium	1277	1·84
Boron	c. 2030	2·5
Carbon	3730	2·25
Iron	1536	7·85
Nickel	1455	8·9
Cobalt	1492	8·71
Chromium	1850	7·2
Niobium	2468	8·55
Molybdenum	2610	10·2
Tantalum	2996	16·6
Tungsten	3410	19·3
Silicon nitride	Sublimes at 1900	3·0
Silicon carbide	Dissociates at 2700	3·1

* Reference to alloys in the text is invariably made to their trade marks or trade names, the originators of which are given in the Appendix. The nominal compositions of commercial and experimental alloys are given in the relevant tables.



Stress temperature distribution along blade aerofoil

Figure A. 5

and reduces precipitation of undesirable phases in the austenitic "face-centered" cubic matrix formed by the alloy. Surface stability is imparted by chronium, protecting the alloy from hot corrosion and oxidation and strengthening the alloy by forming carbides.

Limitations in hot workability will inhibit progress in creep resistance control.

Cobalt-based superalloys are weaker than nickel-based superalloys in the 750-900°C temperature range, are rarely used for first-stage turbine blades but are still found at the second and third stage of the compressor.

1.5.3 Discs

Nickel-iron and nickel-based alloys are the most commonly used alloys for the IP turbine disc stages, such as the Ni-Fe-Cr alloy Incology 901 and 718. HP turbine discs as usually made of Waspoloy. Rene 41, Astroloy and Rene 95 is also used. Also, gatorized integral disc-blade components have been fabricated in IN 100, but mostly for use in missiles. Physical properties of these superalloys are shown in Figs. A. 6.

These materials can be heat treated to develop high-strength properties and low notch sensitivity. Much recent interest has been directed towards powder metallurgy technology, which helps forgeability of the disc and reduces segregation problems. (See Figures A. 6)

Comparative Data on Compressor Blade Materials

Material	Density ρ, 10^3 kg/m^3	UTS σ, MN/m^2	Flexural modulus E, GN/m^2	$\frac{\sigma}{\rho}$, MNm/kg	$\frac{E}{\rho}$, 10^3 GNm/k
Al alloy	2·71	420	69	0·155	25·5
Ti alloy	4·51	1004	124	0·222	27·5
Steel	7·75	1080	207	0·139	26·7
Glass fibre resin	2·05	1130	48	0·550	23·4
Carbon fibre resin (Hyfil)	1·60	1160	165	0·725	103·1

Nominal Chemical Compositions and Densities of Nickel-Base Alloys for Turbine and Compressor Discs

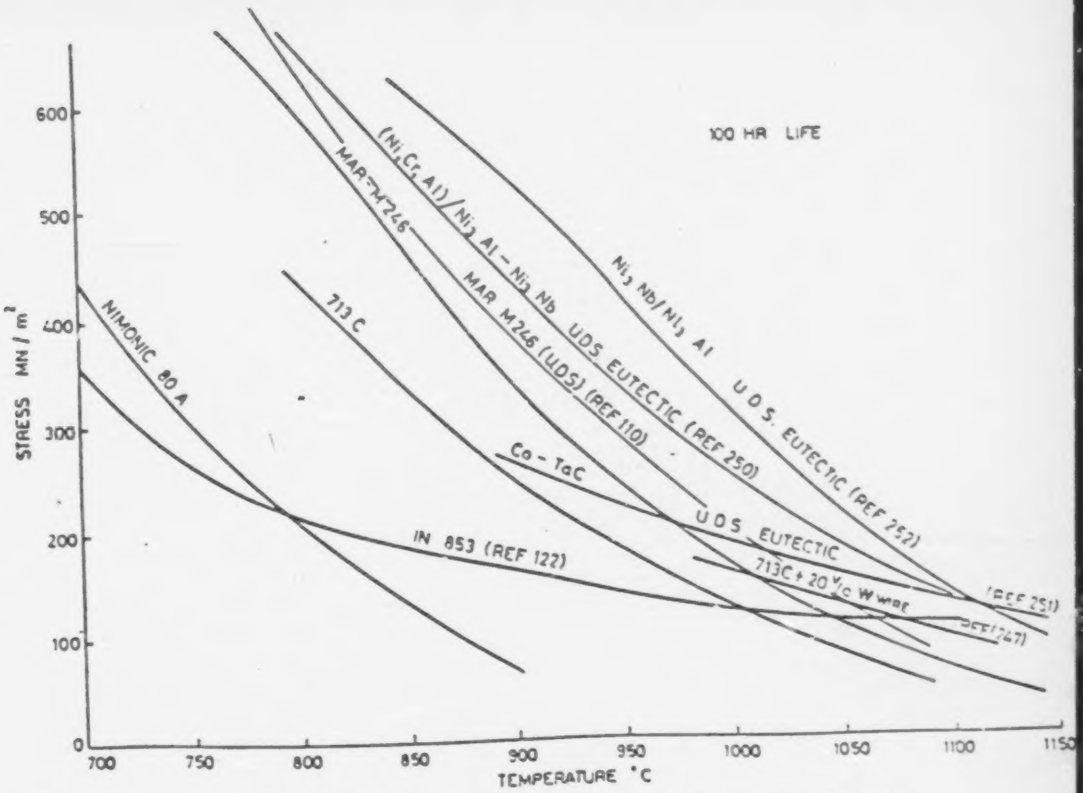
Alloy	Composition, wt-% C	Cr	Co	Al	Ti	Mo	W	Nb	Fe	B	Zr	Density, 10^3 kg m
Incoloy 901	0·05	12·5	—	0·25	2·8	6·0	—	—	42·5	0·015	—	8·22
Inconel 718	0·04	18·6	—	0·4	0·9	3·1	—	5·0	18·5	—	—	8·19
René 41	0·09	19·0	11·0	1·5	3·1	10·0	—	—	5·0 max.	0·007	—	8·25
Nimonic PK 31	0·04	20·0	14·0	0·65	2·6	4·7	—	5·3	—	0·002	0·03	8·35
Waspaloy	0·07	19·5	13·5	1·4	3·0	4·3	—	—	2·0	0·006	0·07	8·19
G81	0·05	19·5	18·0	1·3	2·3	—	—	—	0·5	added	—	8·18
G83	0·10	10·0	10·0	2·0	3·0	10·0	—	—	—	added	added	—
Astroloy	0·06	15·0	15·0	4·4	3·5	5·25	—	—	—	0·03	—	7·90
René 95	0·15	14·0	8·0	3·5	2·5	3·5	3·5	3·5	—	0·010	0·05	8·22
EI 437B	≤0·06	20	—	0·7	2·5	—	—	—	≤4	0·01	—	—
EI 766	≤0·08	16	—	0·7	2	—	—	1·3	≤3	—	—	—
EI 698	≤0·08	14	—	1·2	2·3	2	—	1·8	≤4	—	—	—

Nominal Chemical Compositions and Densities of Cobalt-Base Alloys

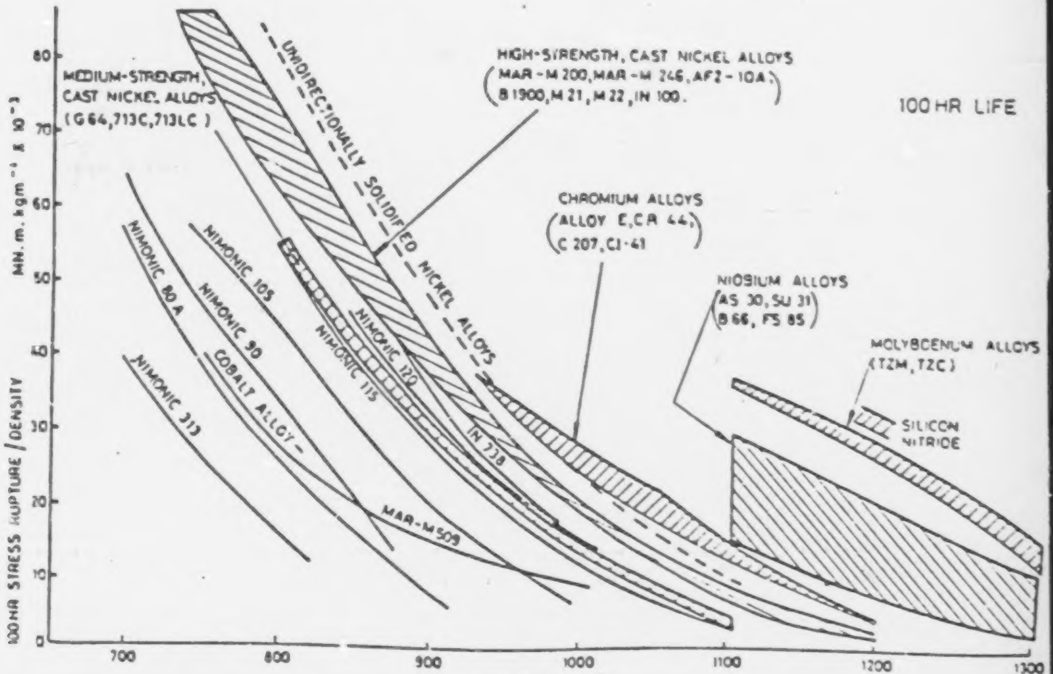
Alloy	Composition, wt-% C	Cr	Ni	Mo	W	Ta	Ti	Al	B	Zr	Fe	Si	Mn	Others	Density, 10^3 kg m^3
Vitallium	0·2	30	—	6	—	—	—	—	—	—	—	—	—	—	8·10
FSX 414	0·25	29·5	10·5	—	7	—	—	—	0·012	—	2 max.	1 max.	1 max.	—	8·30
FSX 418	0·25	29·5	10·5	—	7	—	—	—	0·012	—	2 max.	1 max.	1 max.	0·15Y	—
HS 21	0·25	27	2·75	5·5	—	—	—	—	0·007 max.	—	3 max.	—	—	—	8·30
HS 31 (X 40)	0·5	25·5	10·5	—	7·5	—	—	—	—	—	2 max.	1 max.	1 max.	—	8·61
WI 52	0·45	21	1·0 max.	—	11	2(Ta+Nb)	—	—	—	—	1·75 max.	0·5 max.	0·5 max.	—	8·88
MAR-M 302	0·85	21·5	—	—	10	9	—	—	0·005	0·2	1·5 max.	0·4 max.	0·2 max.	—	9·22
MAR-M 322	1·0	21·5	—	—	9	4·5	0·75	—	—	2·25	0·7	0·2	0·1	—	8·91
MAR-M 509	0·6	23·5	10	—	7	3·5	0·2	—	—	0·5	1·5 max.	0·4 max.	0·1 max.	—	8·86
S 816	0·38	20	20	4	4	4Nb	—	—	—	—	4	—	1·2	—	8·66
AiResist 213	0·18	19	—	—	4·7	6·5	—	3·5	—	0·15	—	—	—	0·1Y	8·50
Haynes 188	0·10	22	22	—	14·5	—	—	—	—	—	3 max.	0·35	1·25 max.	0·09La	9·13

Nominal Chemical Compositions and Densities of Nickel-Base Alloys for Turbine Blades and Nozzle Guide Vanes

Alloy	Composition, wt-% C	Cr	Co	Al	Ti	Mo	W	Nb	Ta	Fe	B	Zr	Others	Density, 10^3 kg/m^3
Nimonic 75	0·10	19·5	—	—	0·4	—	—	—	—	5·0 max.	—	—	—	8·37
Nimonic 80A	0·10 max.	19·5	2·0 max.	1·4	2·5	—	—	—	—	3·0 max.	0·008 max.	0·015 max.	—	8·19
Nimonic 90	0·13 max.	19·5	18·0	1·5	2·4	—	—	—	—	1·5 max.	0·02 max.	0·15 max.	—	8·18
Nimonic 95	0·15 max.	19·5	18·0	2·0	2·9	—	—	—	—	5·0 max.	—	—	—	8·11
Nimonic 100	0·30 max.	11·0	20·0	5·0	1·5	5·0	—	—	—	2·0 max.	—	—	—	8·04
Nimonic 105	0·12	14·8	20·0	4·7	1·2	5·0	—	—	—	1·0 max.	0·007	0·15 max.	—	8·01
Nimonic 108	0·20 max.	14·8	20·0	4·7	1·2	5·0	—	—	—	2·0 max.	0·007	0·15 max.	—	8·01
Nimonic 115	0·15	15·0	14·8	5·0	4·0	4·0	—	—	—	1·0 max.	0·018	0·15 max.	—	7·85
Nimonic 120	0·04	12·5	10·0	4·5	3·5	5·7	—	—	—	0·4 max.	0·03 max.	0·05 max.	—	7·97
M21 (PD 21)	0·10	5·8	1·0	6·0	0·5 max.	2·0	10·5	1·5	—	0·5 max.	0·02	0·12	—	8·53
M22	0·13	5·7	—	6·3	—	2·0	11·0	—	3·0	1·0 max.	—	0·60	—	8·63
M313 (Nimonic 81)	0·06 max.	30·0	—	0·9	1·7	—	—	—	—	2·0 max.	0·003	0·05	—	8·06
MAR-M200	0·15	9·0	10·0	5·0	2·0	—	12·5	1·0	—	—	0·015	0·05	—	8·52
MAR-M246	0·15	9·0	10·0	5·5	1·5	2·5	10·0	—	1·5	—	0·015	0·05	—	8·44
MAR-M002	0·15	9·0	10·0	5·5	1·5	10·0	—	—	2·5	1·0	0·015	0·05	1·5Hf	—
MAR-M004	0·05	12·0	—	5·9	0·6	4·5	—	2·0	—	—	0·010	0·10	1·3Hf	—
MAR-M007	0·10	8·0	10·0	6·0	1·0	6·0	—	—	2·5	—	0·015	0·08	1·3Hf	—
B1900	0·10	8·0	10·0	6·0	1·0	6·0	—	—	4·3	0·35 max.	0·015	0·08	—	8·22
G64	0·13	11·0	—	6·0	—	3·0	4·0	2·0	—	—	0·25	—	—	8·00
GMR 235	0·15	15·5	—	3·0	2·0	5·3	—	—	—	10·0	0·05	—	—	8·03
C242	0·30	20·5	10·0	0·2 max.	0·3 max.	10·5	—	—	—	1·0 max.	—	—	0·3Mn, 0·3Si	8·40
C1023	0·12	14·5	9·0	3·9	3·4	7·5	—	—	—	—	0·004	—	—	—
HRA 376	0·05	6·5	11·5	5·9	—	—	8·5	—	8·5	0·1 max.	0·02	0·10	—	8·85
IN 591-X	0·10	3·0	12·0	5·7	—	—	19·0	—	3·0	—	0·03	0·37	—	9·13
Udimet 500	0·15 max.	17·5	16·5	2·9	2·9	4·0	—	—	—	4·0 max.	0·010 max.	—	—	8·02
Udimet 700	0·15 max.	15·0	17·0	4·3	3·4	5·3	—	—	—	4·0 max.	0·05 max.	—	—	7·91
Unitemp AF2-1DA	0·35	12·0	10·0	4·5	3·0	3·0	6·0	—	1·5	0·5 max.	0·015	0·1	—	8·08
WAZ-20	0·15	—	—	6·2	—	—	18·5	—	—	—	—	1·5	—	9·02
TAZ 8B	0·13	6·0	5·0	6·0	—	4·0	4·0	1·5	8·0	—	0·004	1·0	—	—
IN 713LC	0·12	12·5	—	6·1	0·8	4·2	—	2·2	(Nb + Ta)	—	0·012	0·10	—	7·91
IN 713C	0·05	12·0	—	5·9	0·6	4·5	—	2·0	(Nb + Ta)	0·5 max.	0·01	0·10	—	8·01
IN 100	0·18	10·0	15·0	5·5	4·7	3·0	—	—	—	—	0·014	0·06	1·0V	7·75
IN 587	0·05	28·5	20·0	1·2	2·3	—	—	0·7	—	—	0·003	0·05	—	8·08
IN 738	0·17	16·0	8·5	3·4	3·4	1·8	2·6	0·9	1·8	0·5 max.	0·010	0·10	—	8·11
IN 792	0·21	12·7	9·0	3·2	4·2	2·0	3·9	—	3·9	—	0·02	0·10	Optional 0·5Hf	8·25
IN 853	0·05	20·0	—	1·5	2·5	—	—	—	—	0·2	0·007	0·07	1·3Y_2O_3, 1·2Al_2O_3	8·09
IN 597	0·5	24·5	20·0	1·5	3·0	1·5	—	1·0	—	—	0·012	0·05	—	8·04
Cosint 1000	0·3	16·0	20·0	5·5	2·5	2·5	5·5	—	—	—	0·06	0·2	—	—
NX 188	0·04	—	—	8·0	—	18·0	—	—	—	—	—	—	—	8·19
EI 437B	0·08	20·0	—	0·7	2·6	—	—	—	—	—	0·005	—	—	8·19
EI 867	0·1 max.	9·0	5·0	4·5	—	10·3	5·0	—	—	5·0 max.	0·02 max.	—	0·6V, 0·02$Ce_{max.}$, 0·1$Ba_{max.}$	—
EI 929	0·12 max.	10·5	14·0	4·0	1·7	5·0	5·5	—	—	5·0 max.	0·02 max.	—	0·6V, 0·1$Ba_{max.}$	—
ZhS6-K	0·16	11·0	4·5	5·5	2·8	4·0	5·0	—	—	2·0 max.	0·02	—	—	—

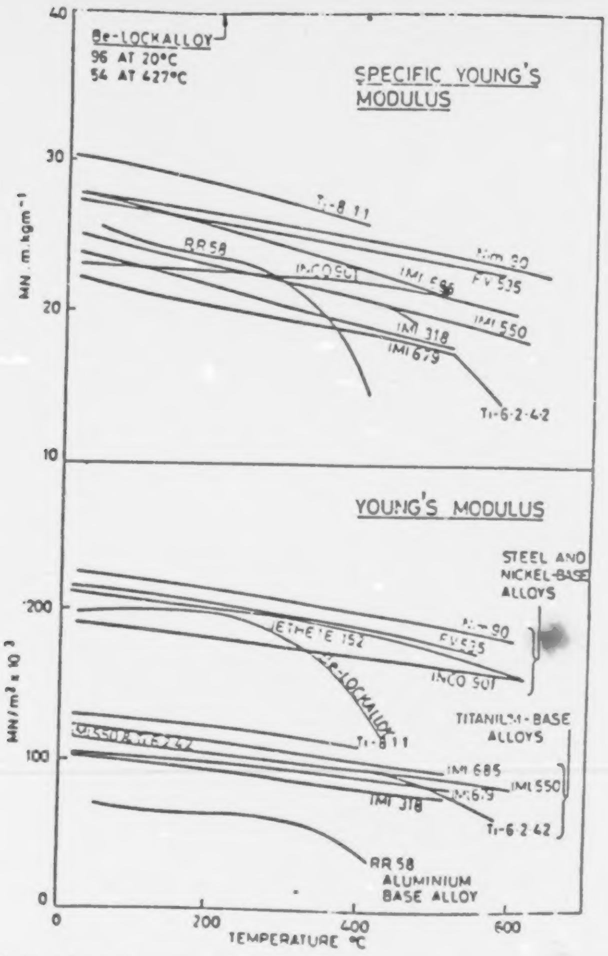


Comparative rupture strength merits of precipitation-, dispersion-, and fibre-strengthened alloys



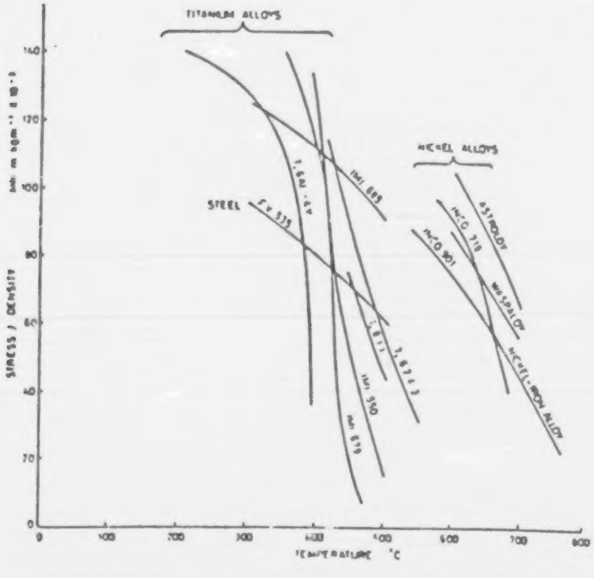
Specific 100 h rupture stress v. temperature for turbine blade materials

Figures A. 6 (5)



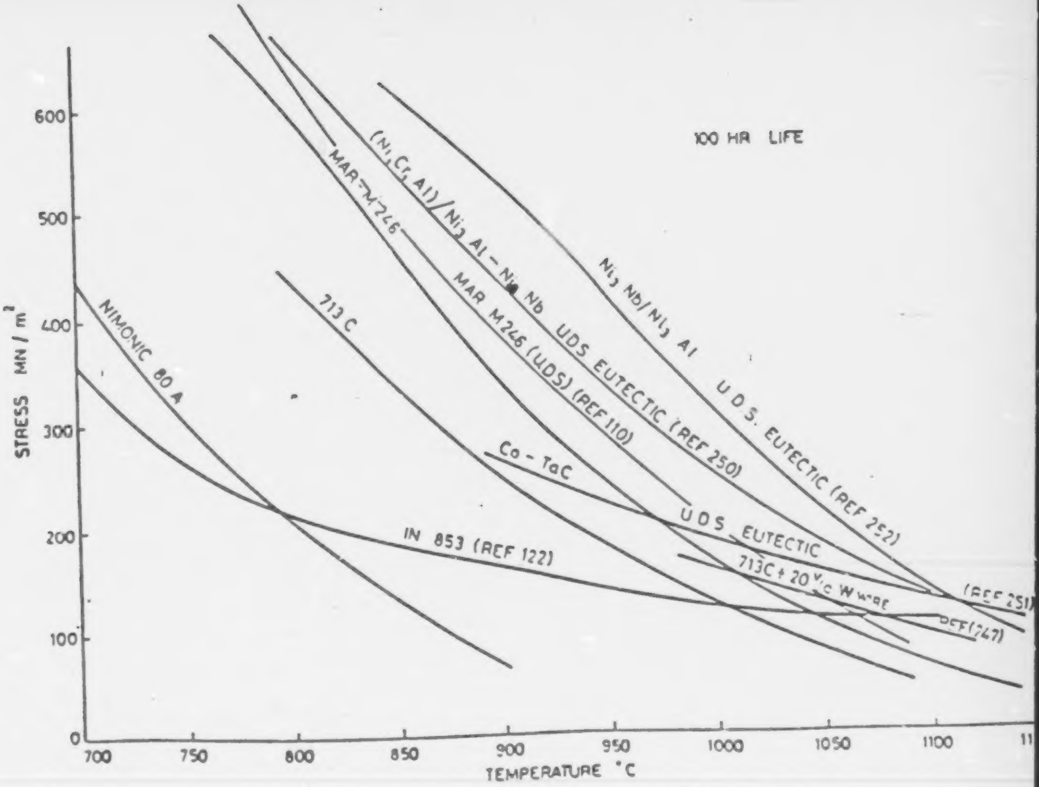
* Modulus and specific modulus v. temperature for compressor blade materials

[Courtesy of Rolls-Royce (1971) Ltd

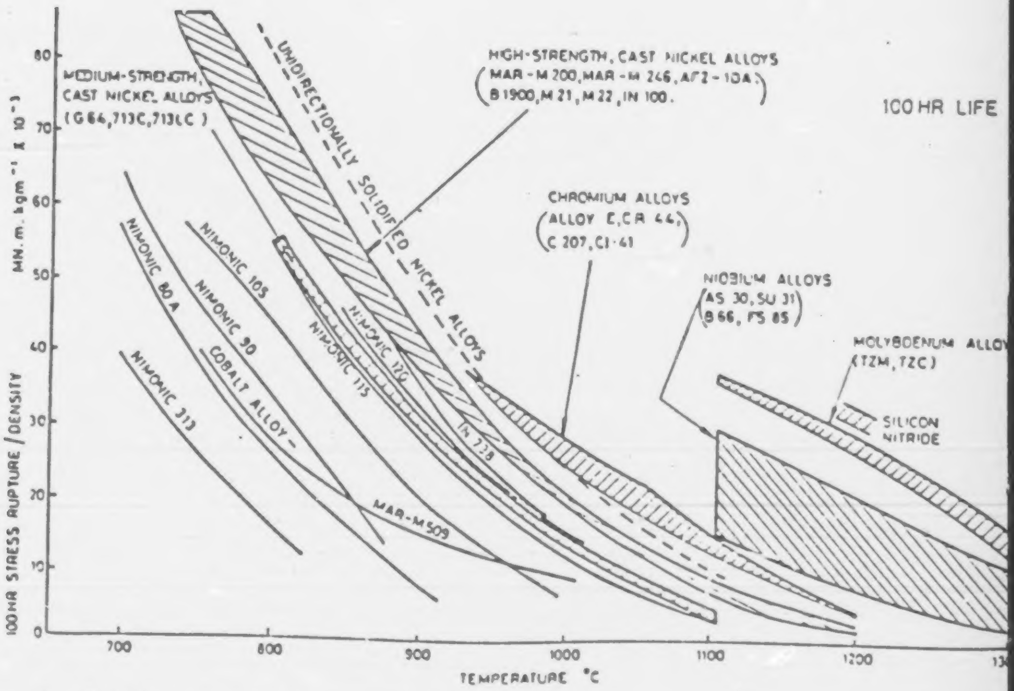


Specific 0·1% creep strain (100 h) v. temperature for compressor and turbine disc materials

Figures A.6 (5)

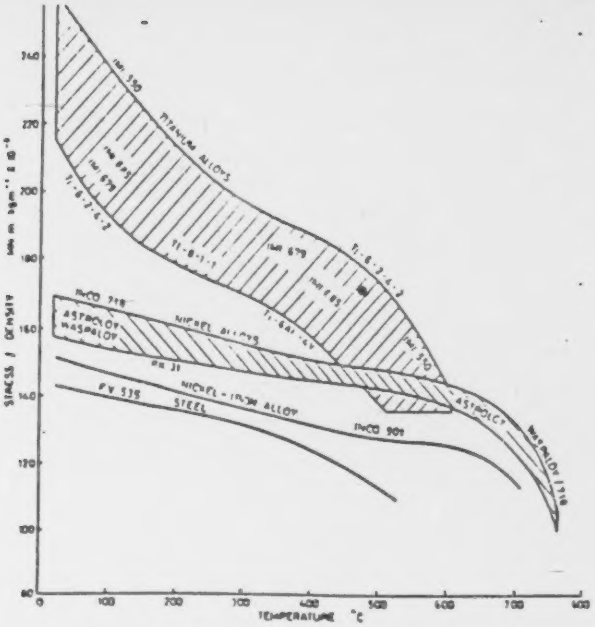


Comparative rupture strength merits of precipitation-, dispersion-, and fibre-strengthened alloys

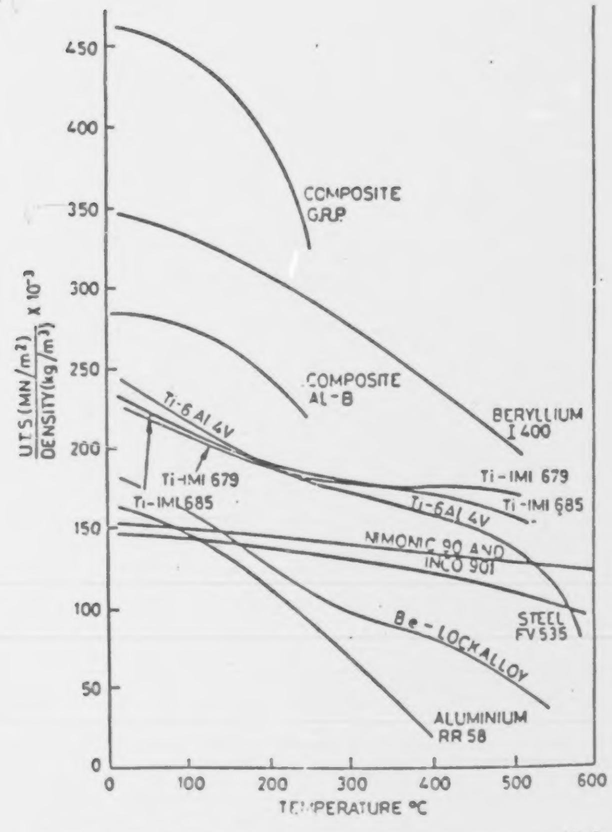


Specific 100 h rupture stress v. temperature for turbine blade materials

Figures A.6 (5)



Specific tensile strength v. temperature for compressor and turbine disc materials



Specific tensile strength v. temperature for compressor blade materials

Figures A.6 (5)

1.5.4 Nozzle Guide Vanes

Cooled and uncooled nozzle guide vanes are usually fabricated from nickel and cobalt-based casting superalloys. Typical stresses of 30-100 MN/m^2 result from gas bending mechanical loads. Failures of these components include bowing (from mechanical loads) local cracking and melting (from thermal shocks), and corrosion/erosion at the leading edge. Both internal cooling and external protection of HP vanes are commonly required.

2. FIBER -REINFORCED SUPERALLOYS FOR HIGH-TEMPERATURE/HIGH-STRESS JET ENGINE APPLICATIONS

2.1 Ceramic/Metal Composites (Refs. 8,9,10,11,13)

Ceramic/Metal composites have the attraction of high strength at high temperature, high modulus and oxidation/corrosion-resistance. Nevertheless, fabrication processes pose enormous practical problems. Ceramic whiskers are difficult to handle and to evenly distribute within the matrix. Stress points easily develop at the fiber-matrix interface. Single crystal fiber technologies have shown equally disappointing properties to date. In particular, disimilar thermal expansion of fiber and matrix cause stress-points within the composite material. Little effective research is currently in progress in this area. Work is currently underway to determine the potential of SiC and B_4C-B filaments in an iron-base alloy matrix for use in the 1400° - 1600° F temperature range. Interfacial reactions between filament and matrix materials occuring during fabrication and service, degrade filament strength. Current research efforts are now focusing on control of these reactions through a low temperature process involving sputtering/wetting of the filaments with a variety of alloys. Results to date have been mixed up to 1600° F, discouraging at 1800° F. Ceramics themselves seem to be a most promising material, but they are for the long-run (8 to 10 years). Ceramics have been well known for thousands of years for their refractory properties and their hardness. Ceramics used in engines would allow to increase the maximum temperature from 1000° C (1830° F) to 1350 or even 1500° C (2460 to 2730° F), and thus to increase the turbine inlet temperature. Such an increase would allow a 20% improvement in engine efficiency. In addition, lower quality fuels might be used.

Superalloys, even improved, are not able to reach such temperatures. A limit seems to be 1100°C (2010°F), and the efficiency of cooling systems cannot be improved much more than currently.

Two ceramics compositions which have been extensively researched, as: silicon nitride (Si_3N_4, pressed and sintered with 2% Al_2O_3 and 4, 6 or 10% Y_2O_3), and silicon carbide (SiC). Research on these two composites is being done in the United States (Garrett, Westinghouse, General Electric, Pratt & Whitney, with contracts from NASA and ERDA), in the United Kingdom, in West Germany (DFVLR, German Office for Aeronautical and Space Researches and Studies, involving

MTU, Volkswagen, Daimler-Benz, etc.), in Sweden, in Japan (Toshiba, in cooperation with Toyota automobiles) and in France.

Advantages of ceramics are their excellent shock resistance and strength at higher temperatures than current superalloys can stand (tensile strength 20 to 30 kg/mm^2 (28,000 to 42,000 psi), compressive strength 200 to 300 kg/mm^2 (283,000 to 425,000 psi), bending strength 30 to 100 kg/mm^2 (42,000 to 141,000 psi). They do not require cooling and manufacturing might be more simple (for blades, a withdrawal process followed by a freezing of the material is used). Another advantage is their low density (2 to 3) which reduces the structural requirement for supporting the centrifugal stresses.

However, the major drawback of ceramics is their brittleness. Current research is attempting to enhance the plasticity of ceramics. The idea is to prevent micro-cracks from expanding by using a suitable structure. Composite ceramics seem to be a solution, one process now in development being particle -dispersed composites. These composites are made of zirconium oxide, which has the property of changing its crystalline structure at 1000 to 1100° C (1800 to 2000° F), with a bigger volume at low temperatures. The material is heated at a temperature higher than this transition temperature, then cooled (sintering process) in the presence of magnesium, calcium or yttrium oxides, which prevent the structural change and stabilize the high temperature structure even below 1000° C. But the key of the process is to be able to allow a certain percentage of grains which are not stabilized and which cannot expand during the cooling only because of their non-expanding environment. If a micro-crack appears, these unstable grains expand into the crack and prevent its propagation. Mastering the cooling process and the optimum percentage of unstable phase is the toughest and most important part of the process.

Another kind of composite is subject to testing in the United States and France. They are alumina-based ceramics in which short fibers of silicon carbides are imbedded, allowing a good plasticity of the material and preventing micro-fissures from expanding.

Processing technologies for simple ceramics are well established. These processes all involves sintering at temperatures typically above 1500° C (2730° F, three quarters of the melting point), which allows grains to aggregate. But for silicon nitride and silicon carbide, this operation must be made under pressure in order to suppress porosity. For small parts, this pressure may be applied along only one direction, but for larger parts, it should be from all directions.

As we said before, ceramics seem to have a promising future, and not only for jet engines. But they are not yet at the industrial stage, and they will probably not reach it before 1990.

2.2 Metal/Metal Composites (Refs. 16-33)

Increasing research efforts are being directed towards developing Metal/Metal composites that will potentially increase operating temperatures in jet engines and contribute towards improving their thermodynamic efficiency. It is believed that this can be achieved while maintaining reliability standards at a modest cost increase in a relatively short period of time. (Figure A. 7)

The current short-term research goal of a number of US institutions is to produce a M/M composite material with increased creep strength at temperatures beyond 2150° F for turbine blade applications. This must be achieved while solving property losses from fiber-matrix inter-diffusion, heat-induced stresses and matrix erosion over long operating time frames. The major benefit of refractory M/M composite's use is to be found in the ductibility of the refractory alloy wire. The degradation of the alloy-wire properties at service temperature is diffusion controlled and closely matches the degradation of high alloyed superalloys. In addition, there is less thermal expansion mismatch as compared to ceramic/metal composites because the refractory wire can relieve strain by plastic deformation rather than fracture.

Molybdenium, niobium, tantalum and tungsten wire have been the main candidates for refractory fiber use.

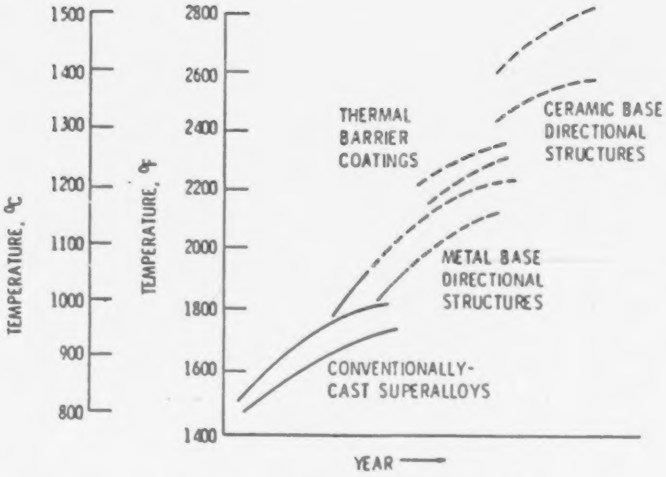


Figure - Higher temperature turbine materials.

Figure A. 7 (30)

The 100-hours rupture strength of W-Re-Hf-C wire at 2000°F was found to be 16 times higher than that of superalloys. Substantial rupture strength improvements are expected in the near future as researchers work to optimize wire property/performance (Figure A. 8). Tungsten fiber reinforced superalloy composites are projected to have the most desirable properties of all candidates considered to date.

Matrix alloy selection has been based on the need to provide fiber-compatibility such that interfacial reactions and bonding characteristics remain favorable under service conditions, while providing oxidation and hot corrosion protection for the tungsten fibers. Adequate low temperature impact resistance and mechanical and thermal fatigue resistance must be provided for as well by the matrix. FeCrAlY, ductible oxidation resistant, iron-base coating alloys have been found to be superior matrix materials as compared to conventional cobalt and nickel based alloys.

Fabrication technologies have been developed to substitute for casting, rolling and forging processing technologies. In particular, diffusion bonding of fiber to matrix powder or foil have offered the best mechanical results in test specimens. For example, 100 hour 2000° F stress-rupture tests have demonstrated that W-Hf-C/FeCrAlY composites are more than three times stronger than conventional superalloys, and that use-

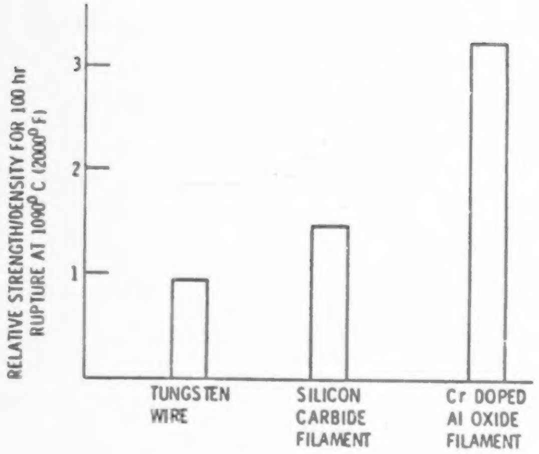


Figure - High temperature fiber strength.

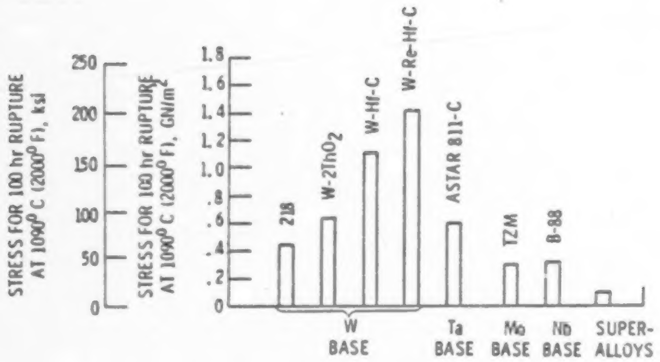


Figure - Refractory alloy wire rupture strength at 1090° C (2000° F).

Figure A 8 (30)

TABLE I. - CHEMICAL COMPOSITION OF WIRE MATERIALS

Material	Weight percent of constituent									
	W	Ta	Mo	Nb	Re	Ti	Zr	Hf	ThO_2	C
Tungsten alloys										
218CS	99.9	-----	---	---	-----	----	-----	----	----	-----
$W-1ThO_2$	bal	-----	---	---	-----	----	-----	----	0.95	-----
$W-2ThO_2$	↓	-----	---	---	-----	----	-----	----	1.8	-----
W-3Re		-----	---	---	2.79	----	-----	----	----	-----
$W-5Re-2ThO_2$		-----	---	---	4.89	----	-----	----	1.76	-----
$W-24Re-2ThO_2$		-----	---	---	[illegible].54	----	-----	----	1.7	-----
W-Hf-C		-----	---	---	-----	----	-----	0.37	----	0.030
W-Re-Hf-C		-----	---	---	4.1	----	-----	.36	----	.021
Tantalum alloys										
ASTAR 811C	8.2	bal	---	---	-----	1.13	-----	.91	----	.027
Molybdenum alloys										
TZM	----	-----	bal	---	-----	.45	0.085	----	----	.031
TZC	----	-----	bal	---	-----	1.18	.27	----	----	.12
Niobium alloys										
FS85	10.44	27.95	---	bal	-----	----	.85	----	----	.031
AS30	20	-----	---	bal	-----	----	1	----	----	-----
B88	28.3	-----	---	bal	-----	----	----	1.94	----	.56

TABLE II. - REPRESENTATIVE PROPERTIES OF REFRACTORY-ALLOY WIRES

Alloys	Density, gm/cm^3	Wire diameter, cm	Ultimate tensile strength		Stress for 100-hr rupture		Stress/density for 100-hr rupture, $cm\times10^3$
			ksi	MN/m^2	ksi	MN/m^2	
A. 1093° C (2000° F) Data							
Tungsten alloys							
218CS	19.1	0.20	126	869	63	434	234
$W-1ThO_2$	19.1	.20	142	979	77	531	282
$W-2ThO_2$	18.9	.38	173	1193	95	655	356
W-3Re	19.4	.20	214	1475	69	476	249
$W-5Re-2ThO_2$	19.1	.20	176	1213	70	483	254
$W-24Re-2ThO_2$	19.4	.20	211	1455	50	345	183
W-Hf-C	19.4	.38	207	1427	161	1110	584
W-Re-Hf-C	19.4	.38	314	2165	205	1413	744
Tantalum alloys							
ASTAR 811C	16.9	.51	108	745	84	579	351
Molybdenum alloys							
TZM	10.0	.20	112	774	42	290	295
TZC	10.0	.13	125	862	38	262	267
Niobium alloys							
FS85	10.5	.13	[illegible]	455	44	303	295
AS30	9.7	.13	[illegible]	421	31	214	224
B88	10.2	.51	[illegible]	[illegible]	[illegible]	331	[illegible]

Alloys	Density, gm/cm^3	Wire diameter, cm	Ultimate tensile strength		Stress for 100-hr rupture		Stress/density for 100-hr rupture, $cm\times10^3$
B. 1204° C (2200° F) Data							
Tungsten alloys							
218CS	19.1	0.20	108	745	46	317	170
$W-1ThO_2$	19.1	.20	122	841	54	372	199
$W-2ThO_2$	18.9	.38	150	1034	70	483	[illegible]
W-3Re	19.4	.20	157	1082	46	317	166
$W-5Re-2ThO_2$	19.1	.20	148	1020	44	303	160
$W-24Re-2ThO_2$	19.4	.20	147	1014	25	[illegible]	[illegible]
W-Hf-C	19.4	.38	201	1386	111	765	404
W-Re-Hf-C	19.4	.39	281	1937	132	910	[illegible]
Tantalum alloys							
ASTAR 811C	16.9	.51	71	490	38	262	157
Molybdenum alloys							
TZM	10.0	.20	77	531	19	131	135
TZC	10.0	.13	79	545	18	124	127
Niobium alloys							
FS85	10.5	.13	40	276	23	159	155
AS30	9.7	.13	33	228	---	----	---
B88	10.2	.51	50	345	28	193	190

Figure A. 8 (30)

temperatures may be increased by up to 320° F over the most performant superalloy in turbine blade applications.

2.2.1 Tungsten Fibers

Tungsten fibers, though they have poor oxidation resistance and high density, can provide superior specific strength qualities to conventional superalloys when enclosed in an oxidation resistant and ductile matrix.

Currently, substantial research efforts are being devoted towards providing tungsten alloy wires with increased strength and improved fiber-matrix compatability over available materials. Tungsten alloy wire have been fabricated having tensile strength 2 1/2 times 218 CS wire currently in use and up to 6 times that of nickel or cobalt based superalloys.

Similarly, excellent progress has been made in providing elevated stress-rupture strength qualities. (for long time applications), 100 hours rupture strengths at 2000° F has been increased from 434 MN/m^2 to 1413 MN/m^2 for W-Re-Hf-C wire (only tantalum alloy wire (ASTAR 811C) is stronger), which has 16 times the strength of superalloys at that temperature. Specific strength of the wire was 7 times that of superalloys as 2000° F and 13 times at 2200° F.

Considerable opportunity still exist to optimize tungsten wire technology in the future.

Figures A.8 show typical data for wire materials.

2.2.2 Matrix Development

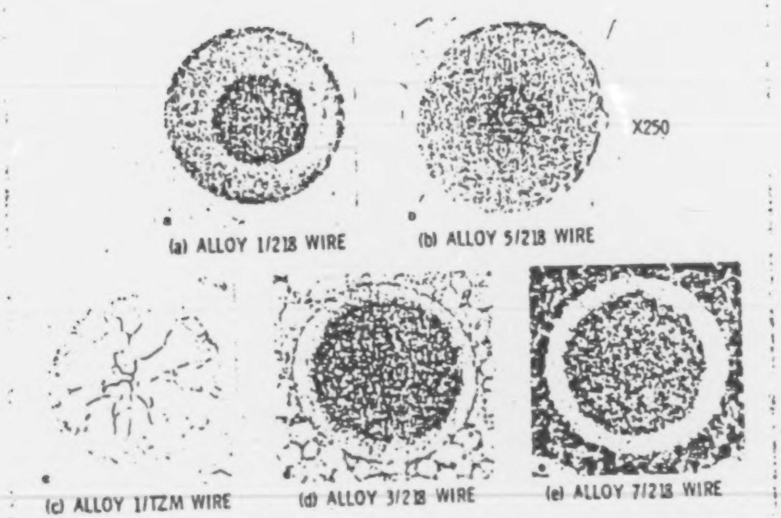
The matrix is exposed to a high temperature, highly corrosive environment from which the refractory wire must be protected. The matrix must also be ductile, compared to the wire, in order to facilitate load transfer from wire to matrix. Also, it must resist abrasion and potential impact from foreign objects. The matrix must also be compatible with the wire such that both do not react, disintegrate, create stress points or degrade wire properties during processing or operation. For high use-temperature, nickel, cobalt and iron-base superalloys have the appropriate strength, ductility, oxidation, and hot corrosion resistance properties to be used as matrices.

Two basic requirements must be fulfilled when choosing a compatible alloy matrix for a given fiber:

1) a strongly bonded interface which allows stress transfer during hot-cold cycles,
2) limited reactions between fiber and matrix during operation to assure adequate service life.

Structurally stable composites are needed such that fiber-matrix compatibility is satisfied: the properties of the fiber should not degrade under processing conditions. Three types of fiber-matrix reactions occur: (Figures A. 9)

1) diffusion-penetration with recrystallization at the fiber-matrix interface.



(a) ALLOY 1/218 WIRE (b) ALLOY 5/218 WIRE

(c) ALLOY 1/TZM WIRE (d) ALLOY 3/218 WIRE (e) ALLOY 7/218 WIRE

CS-82-2309

Figure - Refractory wire/matrix reaction.

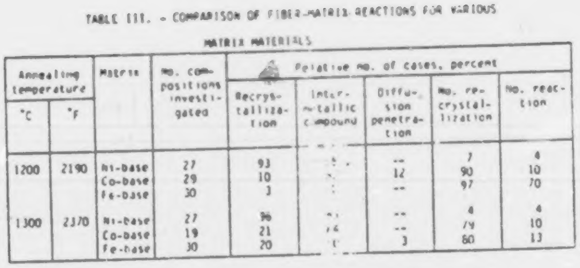


TABLE III. - COMPARISON OF FIBER-MATRIX REACTIONS FOR VARIOUS MATRIX MATERIALS

Annealing temperature		Matrix	No. compositions investigated	Relative no. of cases, percent				
°C	°F			Recrystallization	Intermetallic compound	Diffusion penetration	No recrystallization	No reaction
1200	2190	Ni-base	27	93	[illegible]	--	7	4
		Co-base	29	10	[illegible]	12	90	10
		Fe-base	30	3	[illegible]	--	97	70
1300	2370	Ni-base	27	96	[illegible]	--	4	4
		Co-base	19	21	[illegible]	--	79	10
		Fe-base	30	20	[illegible]	3	80	13

Figure A. 9 (30, 31)

2) Precipitation of a second phase with no recrystallization.

3) Solid solution reaction with no recystallization.

Reaction (1) is by far the most damaging: cobalt and nickel diffuse into the tungsten wire. Superalloys that contain high weight fractions of refractory metal lower the recrystallization temperature of tungsten and reduce diffusion penetration of nickel into tungsten. Alloying with aluminum further serves to reduce diffusion of nickel into tungsten. Alloying with iron reduces the recrystallization. It has been found that no intermetallic compounds are formed when tungsten fibers reinforce an iron-base matrix. Short time exposures of FeCrAlY matrix composites at 2190° F have shown no detectable reactions with the tungsten fibers. Nickel and cobalt based superalloys matrices can require protective barriers between matrix and fiber to inhibit undesirable diffusion.

Formation of intermetallic compounds serve as a natural diffusion barrier at high operations temperature. Deposited coatings (tested to date) have not offered reproducibility results satisfactory to the engines manufacturing and operating community. Studies are continuing in this direction and show potential promise.

In conclusion, though nickel and cobalt based superalloys can be altered to provide acceptable compatibility with tungsten fiber, iron-based superalloys seem to offer a far simpler and more easily reproducible alternative for reinforcement and subsequent usage in jet engines. Additional advantages of these M/M composites over conventional superalloys have been identified.

1) Tungsten has a low thermal expansion coefficient as compared to superalloys and other matrix materials. This leads to less chance of spalling (heated layers flaking off) which can occur from expansion mismatch between the composite and ceramic barrier coats. The ultimate result will be an increase in use-temperature of the materials, and/or a reduction in the need for blade cooling.
2) Tungsten's thermal conductivity is three times that of conventional superalloys and tungsten reinforced superalloys are up to twice as conductive as the superalloy matrix, alone. This results in an increase in potential use-temperature with a subsequent reduction in the need for blade cooling. It may also reduce the need for more complex blade geometries required for film and transportation cooling.

2.2.3 Composite Properties

2.2.3.1 Stress-Rupture Strength

At high temperature, the main contributor to the rupture-strength in a tungsten fiber reinforced superalloy (TFRS) composite comes from the tungsten wire. The degree of strengthening depends on the fiber's strength, the percentage of fiber in the composite, and the degree of fiber-matrix interaction. In general, higher fiber content and stronger individual fibers had lead to higher rupture-strength of the composite material. W-Hf-C fiber systems have proven the strongest to date. 56 percent volume-fraction tungsten-reinforced superalloys have given over 2 times the rupture-strength of conventional FeCrAlY superalloys for 100-hour tests at 2000° F. The specific strength of 40 percent volume fraction tungsten reinforced superalloys have given similar results. For 5000-10,000 hour blade lives, the advantage of these composite materials over conventional superalloys has been more than adequate. They additionally offer a 200° F temperature advantage (in specific terms) over the strongest superalloys. (Figures A. 10)

2.2.3.2 Creep Resistance

In general, fiber reinforcement of conventional materials reduces the second stage minimum creep rate for a given applied stress. Creep deformation can occur at the fiber-matrix interface next to the fracture surface, but this creep phenomena has been found to be well controlled by the good creep resistance of tungsten wire in FeCrAlY and other-matrices. (Figures A. 11)

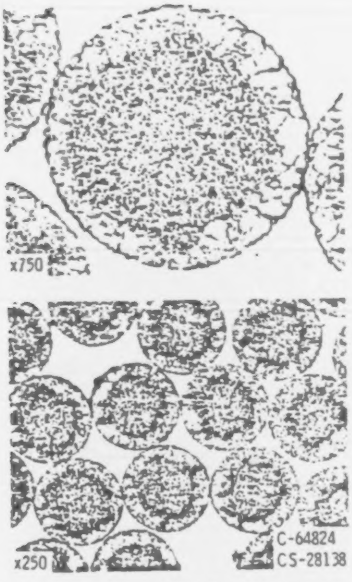


Figure - Recrystallization of tungsten fibers in a copper plus 10 percent nickel matrix. (Ref. 9)

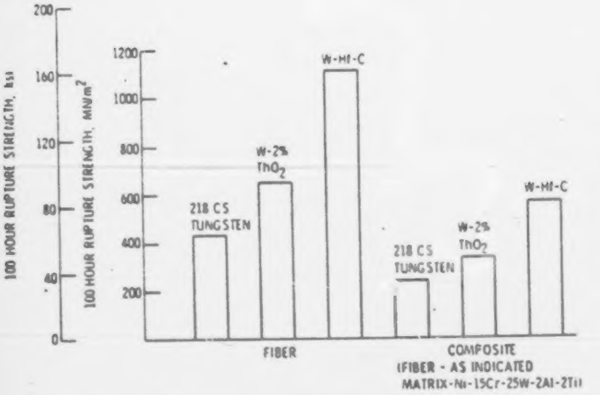


Figure - Comparison of 100 hour rupture strength at 1093° C (2000° F) for fibers and 70 volume percent fiber composites.

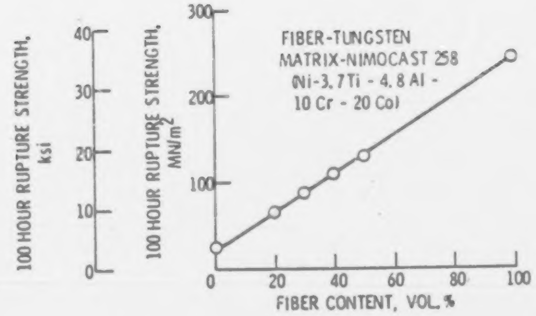


Figure - Effect of fiber content on 100 hour composite rupture strength at 1100° C (2010° F). (Ref. 29)

Figure A.10 (30,31)

TABLE IV. - RUPTURE STRENGTHS AND COMPOSITIONS FOR COMPOSITES AND SUPERALLOYS

A. 100 hr rupture strength at 1100° C (2010° F) for composites and superalloys

Ref.	Alloy	Wire	Wire diam		Vol. %	Density		100 hr rupture strength		Stress-density for 100 hr rupture	
			mm	in.		gm/cc	lb/in.³	MN/m²	ksi	m	in.
30	ZhS6	VRN tungsten	0.3-0.5	0.012-0.020	40	12.5	0.45	138	20	1125	44 300
29 29	EPD-16	---------- tungsten	------- 0.25	---------- 0.010	-- 40	8.3 12.7	0.3 .46	51 131	7.4 19	635 1040	25 000 41 000
31 31	Nimocast 713C	---------- tungsten	------- 1.27	---------- 0.050	-- 20	8.0 10.3	0.29 .37	48 93	7 13.5	613 927	24 000 36 500
19 19	MARM322E	---------- W-2%ThO$_2$	------- 0.08	---------- 0.003	-- 40	---- ----	---- ----	48 207	7 30	---- ----	------ ------
9 9	Ni,Cr,W,Al,Ti	---------- 218CS (tungsten)	------- 0.38	---------- 0.015	-- 40	9.15 13.3	0.33 .48	23 129	3.3 20	254 1058	10 000 41 700
27 28		W-2%ThO$_2$ W-Hf-C	0.38 .38	0.015 .015	40 40	13.0 13.3	0.47 .48	193 324	28 47	1513 2491	59 600 98 000
14	FeCrAlY	W-1%ThO$_2$	0.38	0.015	56	12.5	0.45	831 hr rupture strength-242 MN/m² (35 ksi)		1957	77 000
32	FeCrAlY	W-Hf-C	0.38	0.015	25	11.3	0.41	242	35	2187	[illegible]

B. Nominal composition of matrix alloys (weight %)

Alloy	Composition
ZhS6	Ni-12.5Cr-4.8Mo-7W-2.5Ti-5Al
EPD-16	Ni-6Al-6Cr-2Mo-11W-1.5Nb
Nimocast 713C	Ni-12.5Cr-6Al-1Ti-4Mo-2Nb-2.5Fe
MARM322E	Co-21.5Cr-25W-10Ni-0.8Ti-3.5Ta
Ni,Cr,W,Ti,Al	Ni-15Cr-25W-2Ti-2Al
FeCrAlY	Fe-24Cr-5Al-1Y

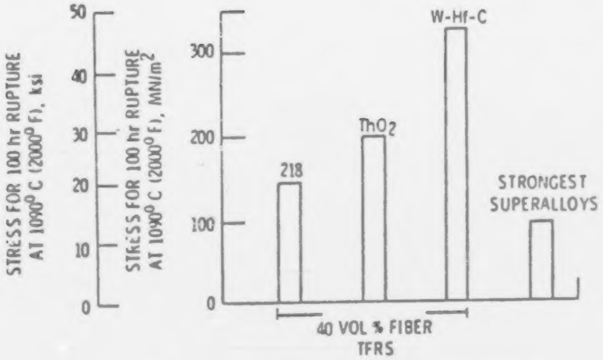


Figure - TFRS composite rupture strength at 1090° C (2000° F).

Figure A. 10 (30,31)

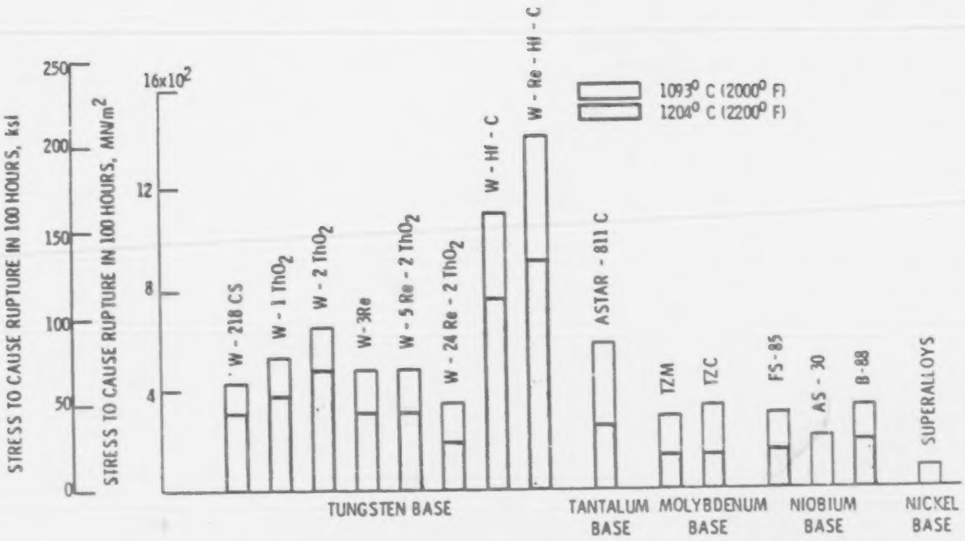


Figure - Stress to cause rupture in 100 hours for refractory metal wires and superalloys. (Refs. 3 and 4)

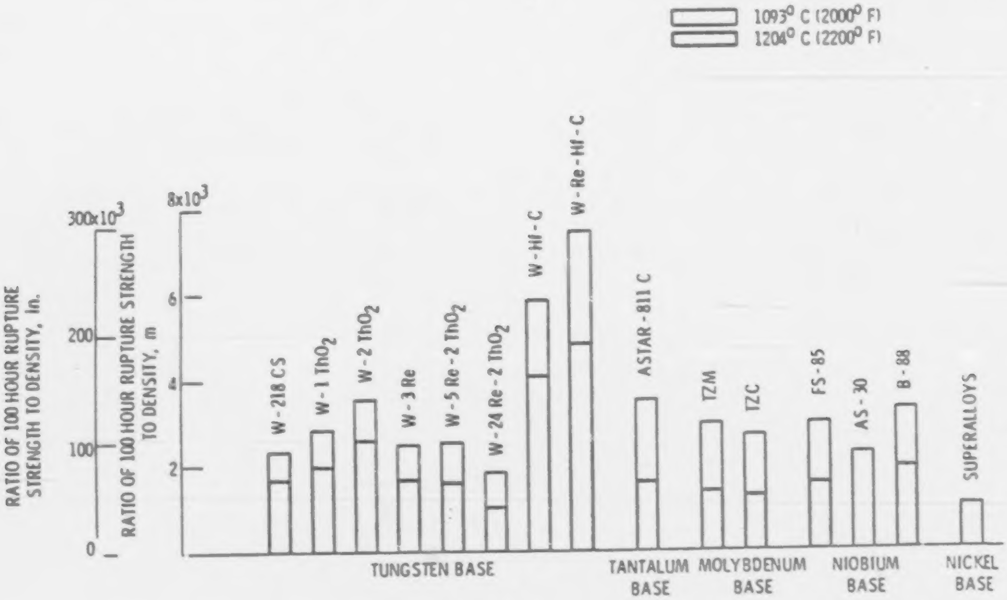


Figure - Ratio of 100 hour rupture strength to density for refractory metal wires and superalloys. (Refs. 3 and 4)

Figure A. 10 (30,31)

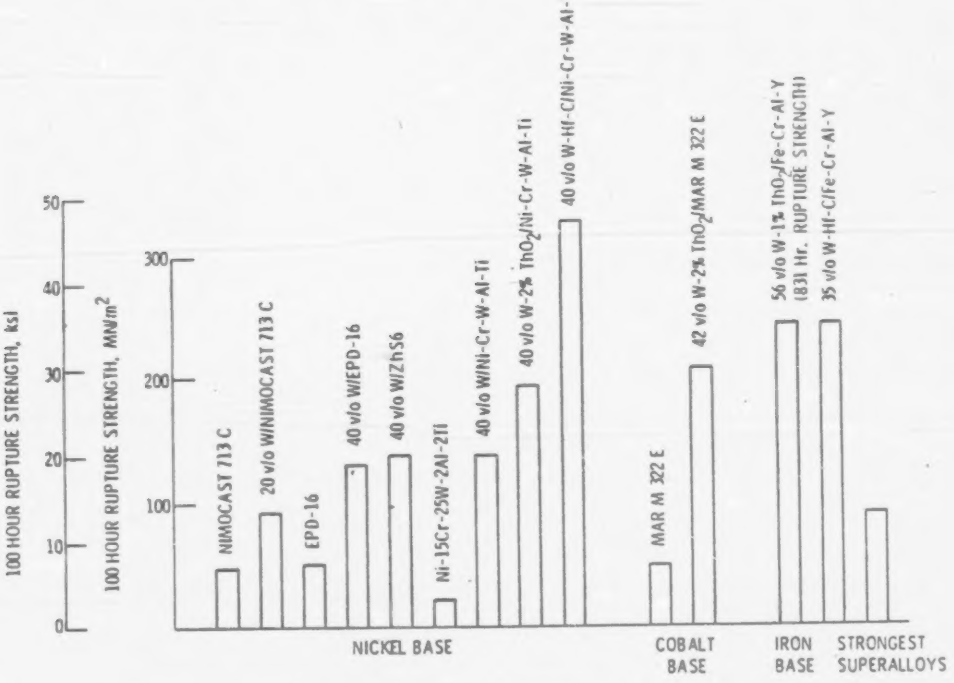


Figure - Comparison of 100 hour rupture strength at 1093° C (2000° F) for composites and superalloys.

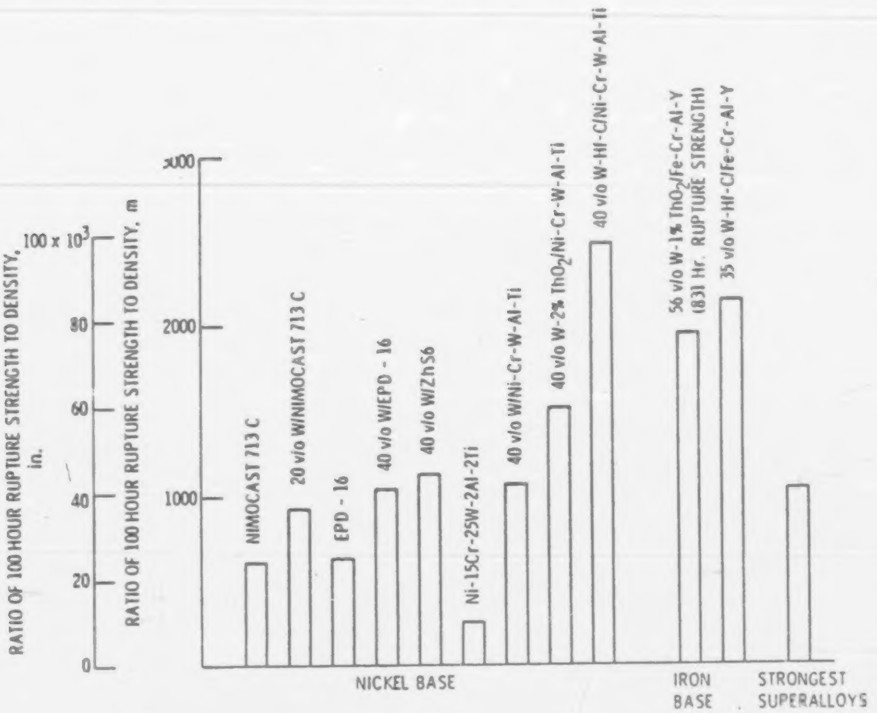


Figure - Comparison of the ratio of 100 hour rupture strength to density for composites and superalloys at 1093° C (2000° F).

Figure A.10 (30,31)

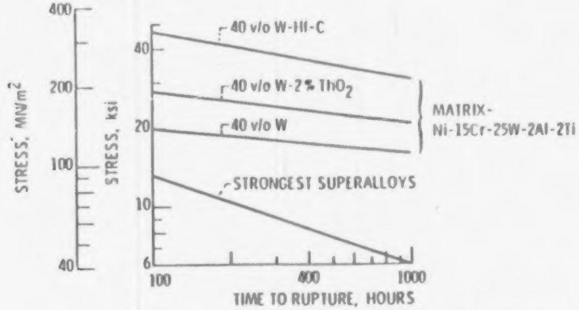


Figure - Stress versus time to rupture comparison for composites and superalloys at 1093° C (2000° F).

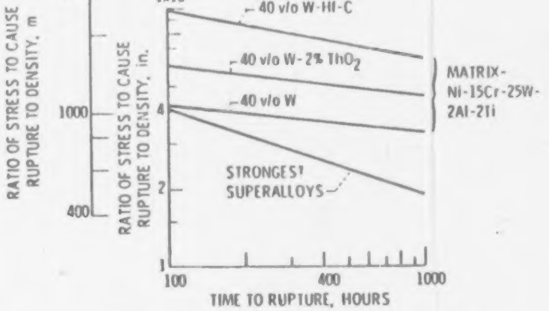


Figure - Stress (to cause rupture) to density ratio for composites and superalloys at 1093° C (2000° F).

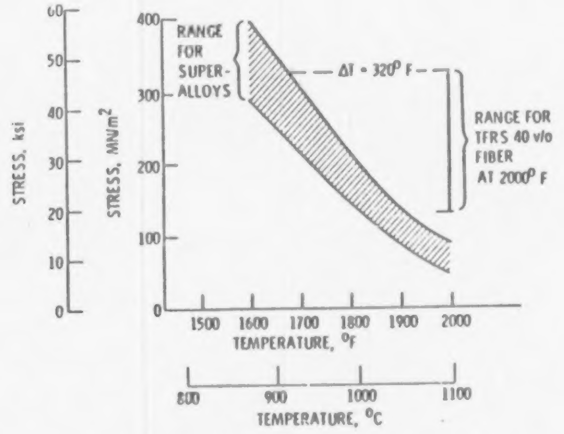


Figure - Comparison of 100 hour rupture strength for TFRS and superalloys.

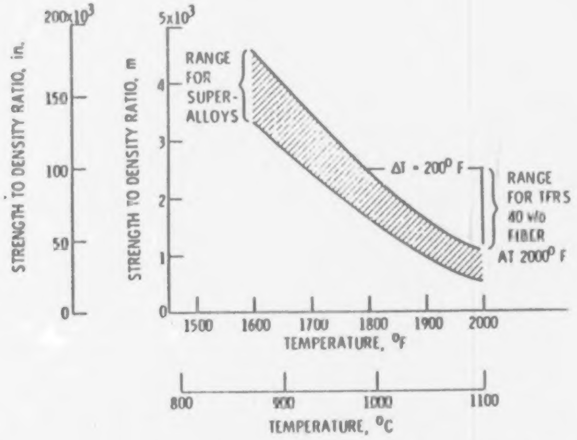


Figure - Comparison of the ratio of 100 hour rupture strength to density for TFRS and superalloys.

Figure A.10 (30,31)

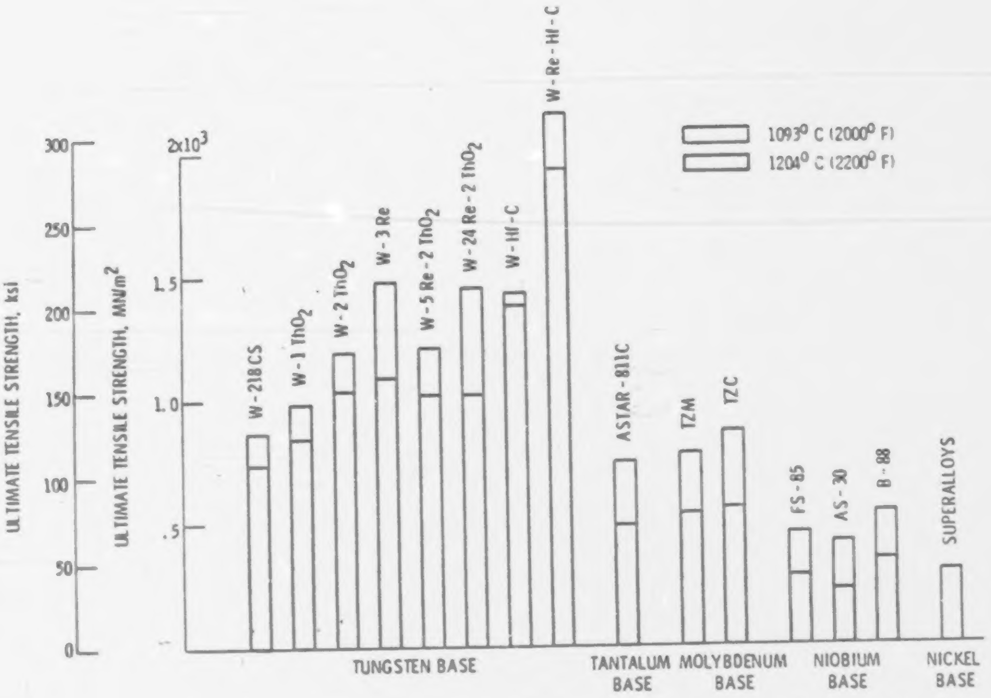


Figure ' - Ultimate tensile strength for refractory metal wires and superalloys. (Refs. 3 and 4)

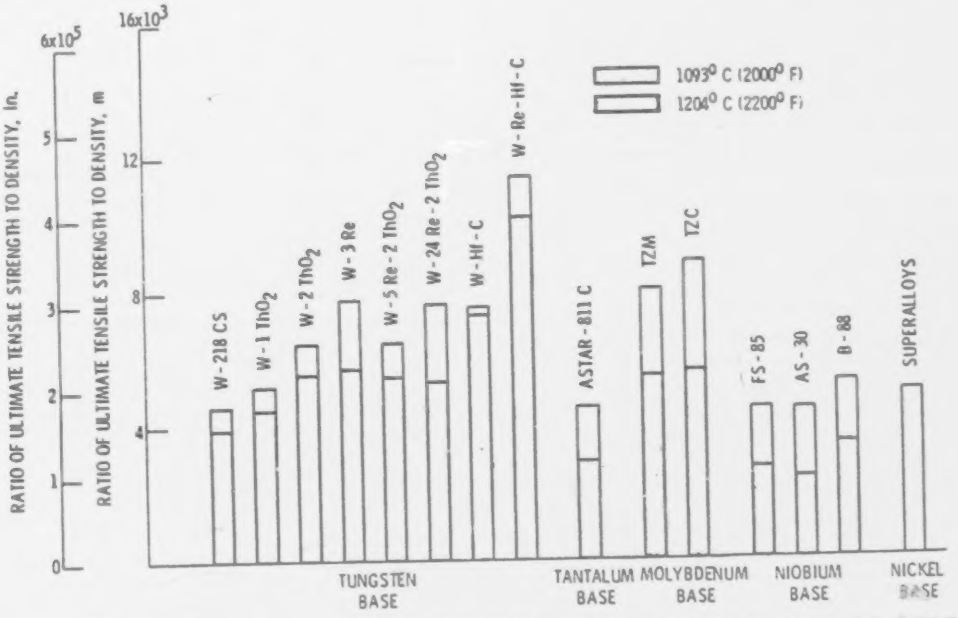


Figure - Ratio of ultimate tensile strength to density for refractory metal wires and superalloys. (Refs. 3 and 4)

Figure A. 10 (30,31)

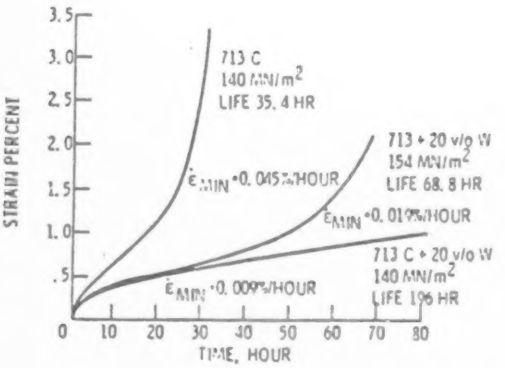


Figure - Comparison of typical creep behaviour of Nimocast 713C with and without tungsten reinforcement at 1100° C (2010° F). (Ref. 31)

Figure A. 11 (31)

2.2.3.3 High Cycle Fatigue

High cycle fatigue occurs due to acyclic mechanical loads that create localized plastic deformation within the materials. In composite materials, this phenomena is controlled by the fiber reinforcement. Unidirectionally reinforced tungsten (with 1% ThO_2)/ Hastalloy composites (23, 30 and 37% volume fiber) were tested against unreinforced Hastalloy and were shown to posses 1.2 times superior fatigue strength to ultimate tensile strength at temperatures ranging from 1500° to 1800° F. Similarly positive results were obtained with W-1% ThO_2/FeCrAlY composites. (Figures A. 12)

2.2.3.4 Low Cycle Fatigue

Low cycle fatigue occurs due to high stress cyclic loads after a small number of load cycle, creating layer scale yielding. Experimental results seem to indicate that the reinforcing fiber enhances low cycle fatigue strength. (Figures A. 12)

2.2.3.5 Thermal Fatigue

Thermal fatigue failure occurs because of thermal stresses and strains due to rapid transient temperature changes and gradients in a material (e.g. a turbine engine blade), forming cracks and potential catastrophic failures. In composite materials, this affect may be compounded by internal stresses due to differences in the thermal expansion coefficients between fiber and matrix. Because the thermal expansion coefficients of tungsten

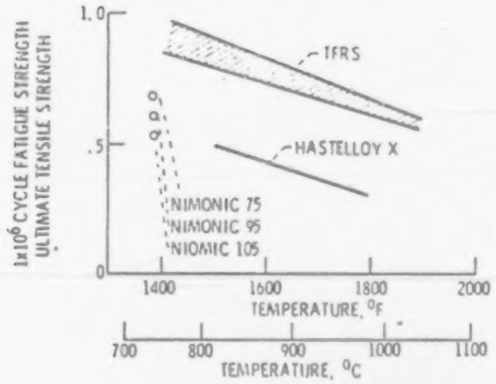


Figure - Comparison of high-cycle fatigue strength ratio for TFRS and superalloys.

Figure A. 12 (30)

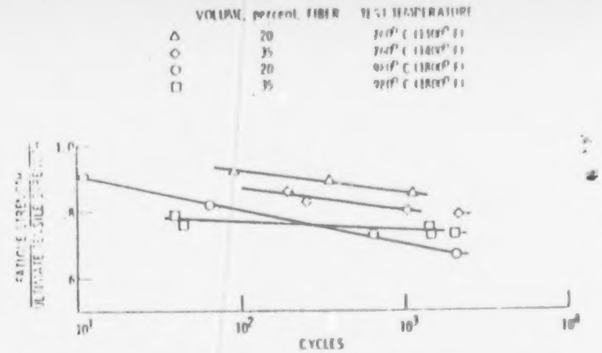


Figure - Ratio of fatigue strength to ultimate tensile strength versus cycles to failure for W-1% ThO_2/FeCrAlY composites. (Ref. 36)

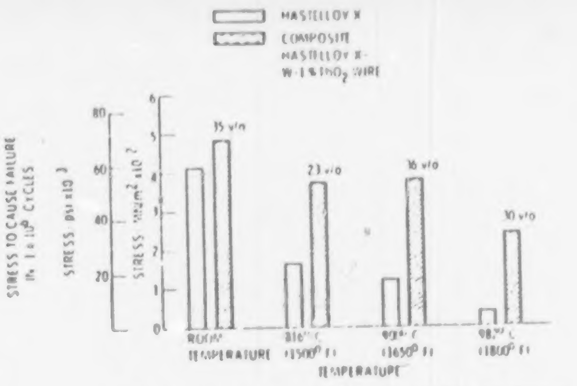


Figure - Stress for failure in 1x10^6 cycles for Hastelloy X and composite (Ref. 33)

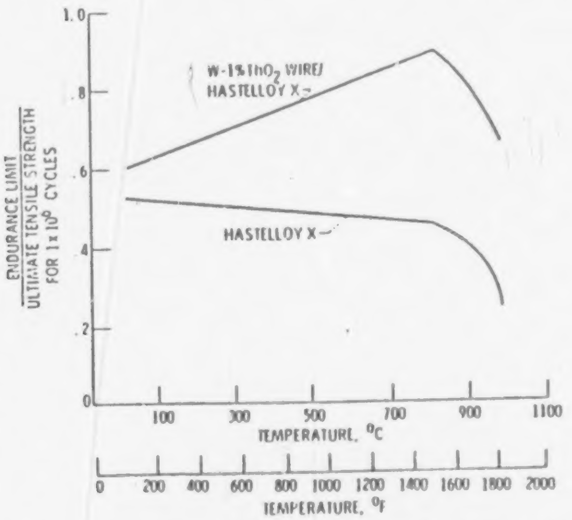


Figure - Ratio of endurance limit to ultimate tensile strength for Hastelloy X and composite tested in axial tension-tension. (Ref. 33)

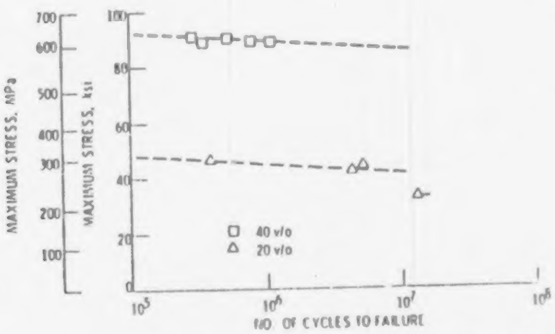


Figure - Stress as a function of number of cycles to failure for W-1% ThO_2/FeCrAlY composites tested at 760° C (1400° F). (Ref. 36)

Figure A. 12 (30,31)

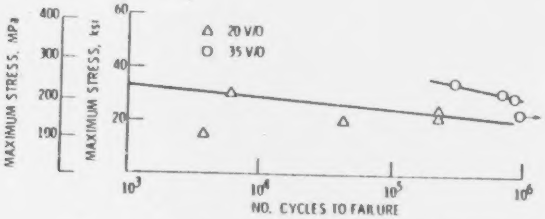


Figure - Stress as a function of number of cycles to failure for W-1%ThO$_2$/FeCrAlY composites tested at 1038° C (1900° F). (Ref. 36)

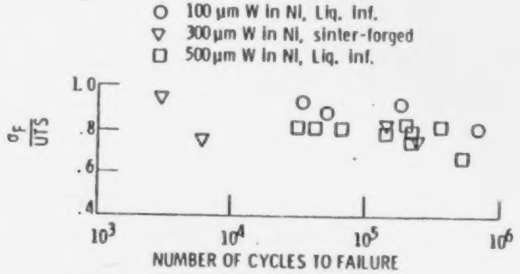


Figure - Ratio of fatigue strength (σ_F) to ultimate tensile strength (UTS) for Ni/W continuously reinforced composites. (Ref. 38)

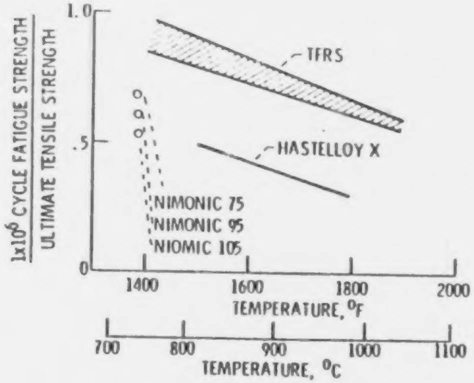


Figure - High-cycle fatigue strength ratio comparison for TFRS and superalloys.

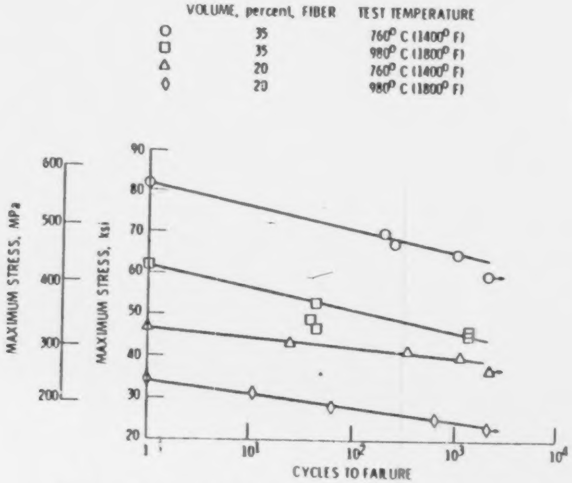


Figure - Maximum stress versus cycles to failure for W-1%ThO$_2$/FeCrAlY composites. (Ref. 36)

Figure A. 12 (31,31)

wire and superalloy matrix are radically different* (6 to 12 orders of magnitude) the resulting thermal fatigue potential is considered one of the most serious limitations to use of these composite materials. (Figure A.13)

The larger the volume fraction of wire, the higher the stress on the matrix upon heating. A ductile matrix must be chosen which can relieve thermally induced strains by plastic deformation.

Experimental results using 30% volume fraction tungsten-1% ThO_2/FeCrAlY have shown evidence of surface roughening but no cracking at test cycle temperature ranging up to 2200° F. Tests on other matrix materials are being carried out. This is still an active area where research needs to be done.

2.2.3.6 Impact Strength

Jet engine blades and vanes must be fabricated with materials that can resist impact failure from foreign objects and failed components passing through the engine. (Figure A.14)

Experimental research results have shown that impact strength in tungsten reinforced superalloys increases with increasing fiber content at high temperatures but decreases at lower temperatures. The major contributor to impact strength at low temperatures is the matrix. At

---

* The wire is strained in compression upon cooling and tension upon locating heating. The matrix is strained in compression upon heating and tension upon cooling.

1000 CYCLES 30°-1200° C (85°-2200° F)

Figure - Photomicrographs of thermally cycled tungsten wire reinforced FeCrAlY composite. (Photos courtesy of Irving Machlin). (Ref. 45)

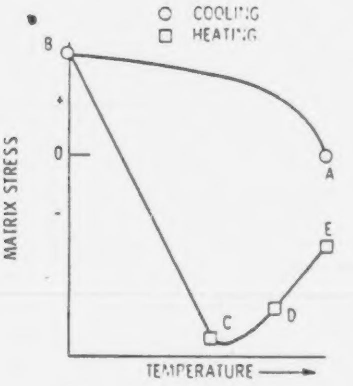


Figure - Matrix stress as a function of heating and cooling.

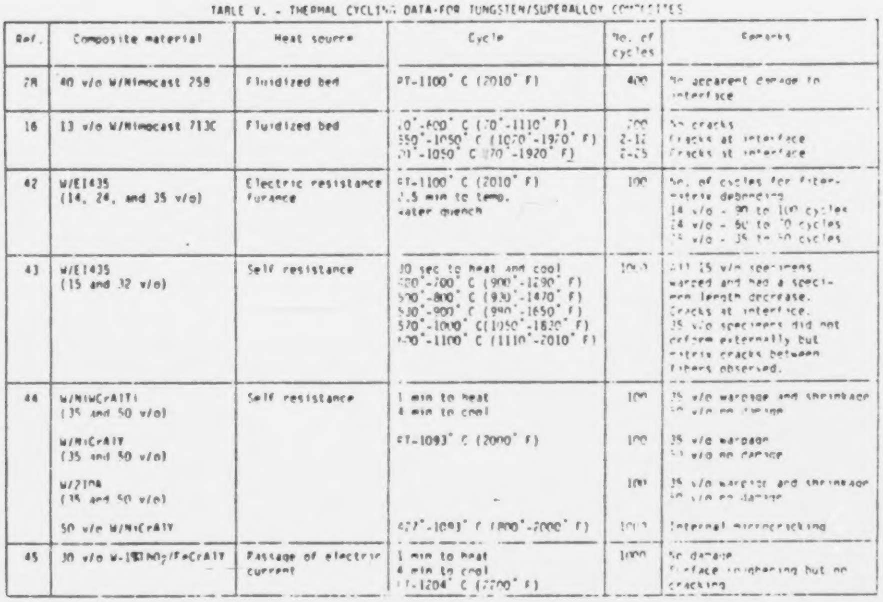
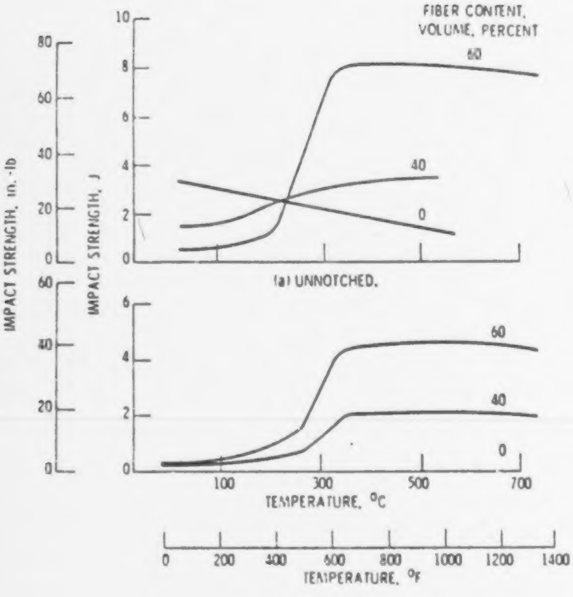


TABLE V. - THERMAL CYCLING DATA FOR TUNGSTEN/SUPERALLOY COMPOSITES

Ref.	Composite material	Heat source	Cycle	No. of cycles	Remarks
28	40 v/o W/Nimocast 258	Fluidized bed	RT-1100° C (2010° F)	400	No apparent damage to interface
16	13 v/o W/Nimocast 713C	Fluidized bed	20°-600° C (70°-1110° F) 550°-1050° C (1020°-1920° F) 20°-1050° C (70°-1920° F)	200 2-12 2-25	No cracks Cracks at interface Cracks at interface
42	W/EI435 (14, 24, and 35 v/o)	Electric resistance furnace	RT-1100° C (2010° F) 2.5 min to temp. water quench	100	No. of cycles for fiber-matrix debonding 14 v/o - 90 to 100 cycles 24 v/o - 60 to 70 cycles 35 v/o - 35 to 50 cycles
43	W/EI435 (15 and 32 v/o)	Self resistance	30 sec to heat and cool 480°-700° C (900°-1290° F) 500°-800° C (930°-1470° F) 530°-900° C (990°-1650° F) 570°-1000° C(1050°-1830° F) 600°-1100° C (1110°-2010° F)	1000	All 15 v/o specimens warped and had a specimen length decrease. Cracks at interface. 35 v/o specimens did not deform externally but matrix cracks between fibers observed.
44	W/NiWCrAlTi (35 and 50 v/o)	Self resistance	1 min to heat 4 min to cool	100	35 v/o warpage and shrinkage 50 v/o no damage
	W/NiCrAlY (35 and 50 v/o)		RT-1093° C (2000° F)	100	35 v/o warpage 50 v/o no damage
	W/Z104 (35 and 50 v/o)			100	35 v/o warpage and shrinkage 50 v/o no damage
	50 v/o W/NiCrAlY		427°-1093° C (800°-2000° F)	1000	Internal microcracking
45	30 v/o W-1%ThO$_2$/FeCrAlY	Passage of electric current	1 min to heat 4 min to cool RT-1204° C (2200° F)	1000	No damage Surface roughening but no cracking

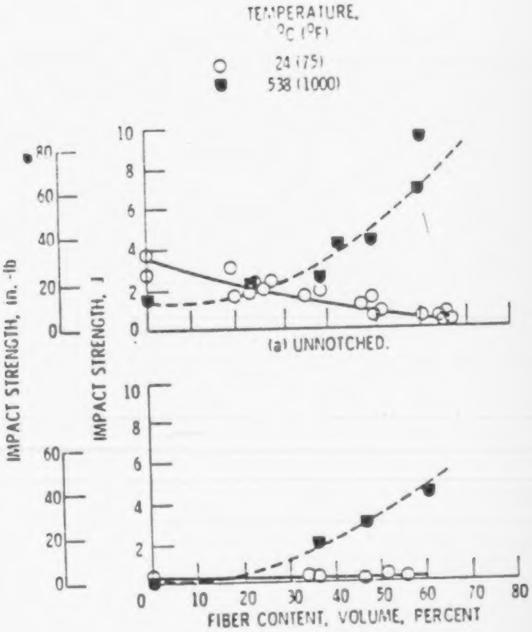
Figure A. 13 (30,31)



(a) UNNOTCHED.

(b) NOTCHED.

Figure - Impact strength of unnotched and notched tungsten/superalloy as function of temperature and various fiber contents. (Ref. 53)



(a) UNNOTCHED.

(b) NOTCHED

Figure - Impact strength of unnotched and notched as-HIP tungsten/superalloy as a function of fiber content. (Ref. 53)

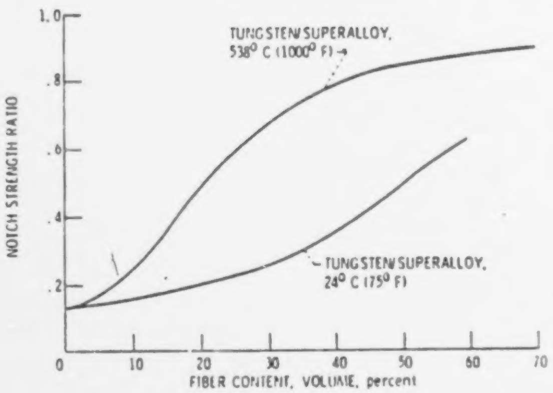


Figure . - Notch strength ratio as function of fiber content for tungsten/metal composites tested at 24 and 538° C (75° and 1000° F). (Ref. 53)

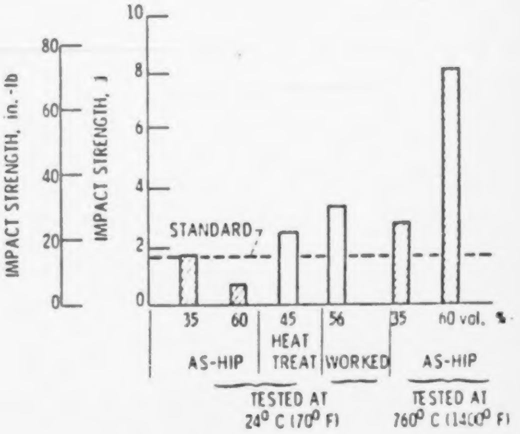


Figure - Miniature Izod impact strengths of unnotched tungsten/nickel-base superalloys compared to minimum impact strength standard used to screen potential turbine blade and vane materials. (Ref. 53)

Figure A. 14 (30,31)

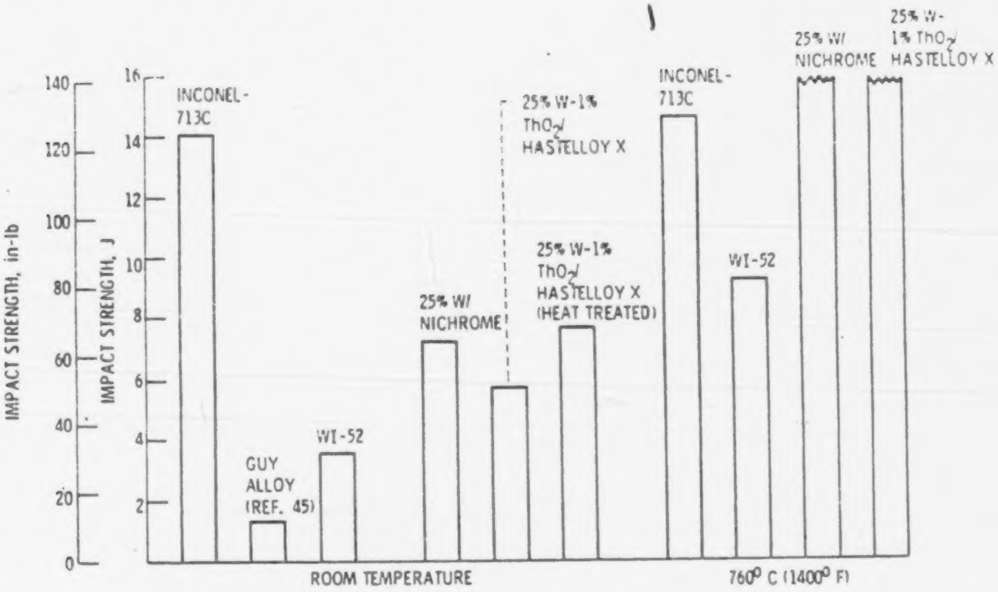
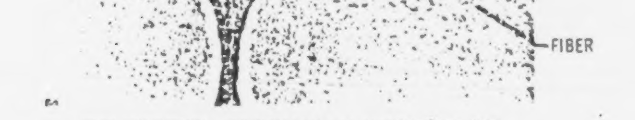


Figure - Miniature Izod impact strength for superalloys and composites.



TEST CONDITION - EXPOSED TO AIR ATMOSPHERE FOR 50 HR AT 2000° F

Figure . - Transverse section of oxidized refractory fiber - nickel alloy composite. (Ref. 27)

Figure A.14 (30,31)

higher temperatures (>500°F) the wire properties predominate. Also, notch sensitivity of the composite decreases with increasing fiber content. Heat treatment and hot rolling improves low temperature impact strength. Tests of heat treated 40 to 60 percent fiber content superalloys were found to meet or exceed minimum impact values at temperatures approaching 2000° F.

2.2.3.7 Oxidation/Hot Corrosion

Gas turbine engines are subject to oxygen partial pressures of 2-4 atm. and significant amounts of combustion and air intake impurities (e.g. sulfur, alkali salts). Sulfides and oxides may thus form within the alloy, leading to serious oxidation and hot corrosion problems. (Figure A.15)

In a tungsten reinforced/superalloy system, the superalloy can be expected to provide sufficient oxidation resistance for itself and the tungsten wires at operating temperatures up to 1800° F. Between 1800° F and 2000° F., the superalloy must be coated with an oxidation resistant NiCrAlY or FeCrAlY superalloy (E.G. Inconel). Though oxidation and hot corrosion conditions have not been shown to severely degrade the characteristics of the composite, this area is still a major source of concern for potential end-users and may contribute a serious barrier to implementation.

2.2.3.8 Thermal Conductivity

The conductivities of tungsten wire reinforced superalloys are significantly higher than those of conventional

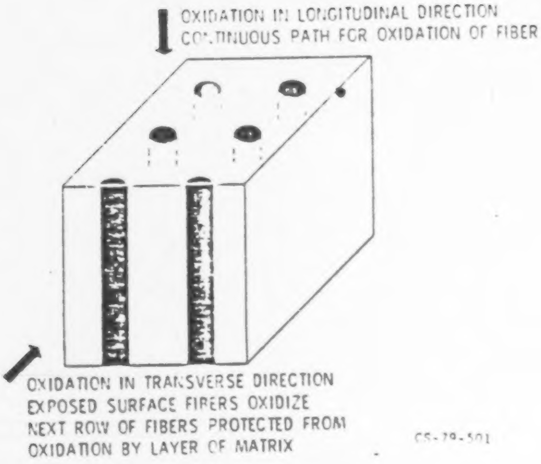

OXIDATION IN LONGITUDINAL DIRECTION
CONTINUOUS PATH FOR OXIDATION OF FIBER
OXIDATION IN TRANSVERSE DIRECTION
EXPOSED SURFACE FIBERS OXIDIZE
NEXT ROW OF FIBERS PROTECTED FROM
OXIDATION BY LAYER OF MATRIX
CS-79-501

Figure - Principal paths for exposed fiber oxidation.

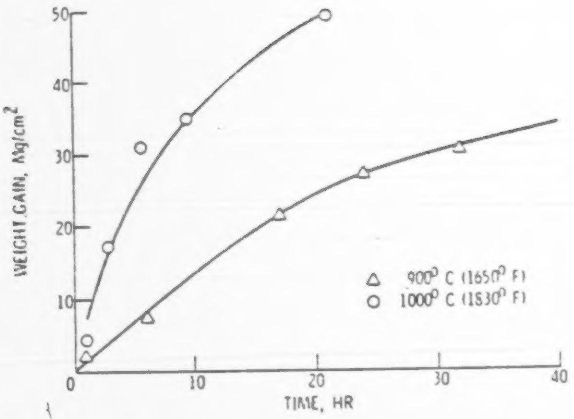


Figure . - Weight gain-time curves for the oxidation of W-reinforced Ni-20Cr at 900 and 1000° C (1650 and 1830° F) containing end exposed fibers. (Ref. 50)

Figure A. 15 (30, 31)

superalloys at all temperatures, because tungsten is far more heat conductive than superalloys. This is a desirable attribute in turbine blade applications because it reduces temperature gradients and thermally induced strains in the blade. A secondary benefit is that higher conductivity reduces the cooling requirement in impingement cooled blades. This serves to increase the lifetime and efficiency of the engine.

Because of its higher conductivity, the higher the volume content of tungsten in the composite, the higher the conductivity of the system, especially in the direction of the wire axis. (Figures A. 16)

2.2.4 Component Fabrication (Figures A. 17)

Currently the most cost effective and reproducible fabricatio technology for tungsten reinforced superalloy hollow turbine blades is diffusion bonding of monolayer composite piles of aligned tungsten wires between layer of superalloy material. This technology offers a number of distinct advantages over other technologies (e.g. investment casting):

1) accurate fiber alignment and distribution
2) reduced wire-matrix interdiffusion during processing
3) blade shapes close to final dimensions

Successful fabrication of tungsten-1%ThO_2/FeCrAlY blades have been achieved at a manufacturing cost competitive with directional solidification technology. (Figure A. 17)

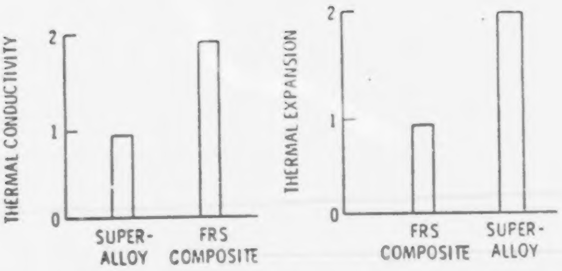


Figure 1 - Relative thermal conductivity and thermal expansion advantage of FRS over superalloys; condition: typical blade temperatures.

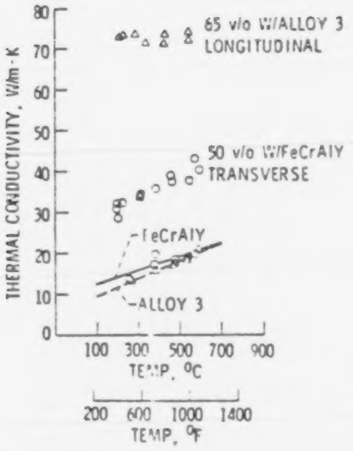


Figure . - Measured thermal conductivity of TFRS composites and matrix alloys. (Ref. 53)

Figure A. 16 (30, 31)

BENEFITS

- HIGHER PRODUCTION RATES-AUTOMATED
- CLEANER MATRIX-HIGHER STRENGTH
- LOWER COST
- IDEAL FOR NEW MATRIX DEVELOPMENT

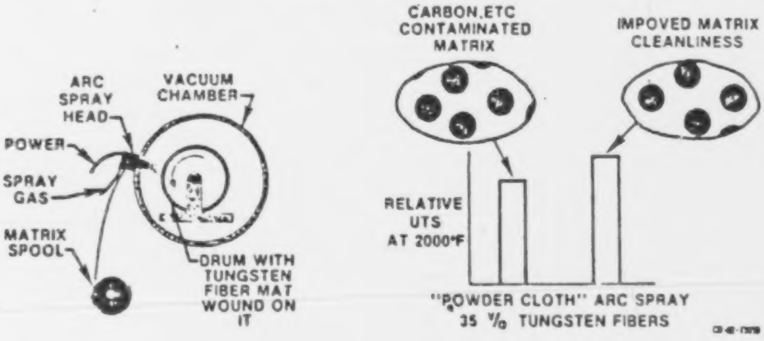

ARC SPRAY HEAD
VACUUM CHAMBER
POWER
SPRAY GAS
MATRIX SPOOL
DRUM WITH TUNGSTEN FIBER MAT WOUND ON IT
CARBON,ETC CONTAMINATED MATRIX
IMPOVED MATRIX CLEANLINESS
RELATIVE UTS AT 2000°F
"POWDER CLOTH" ARC SPRAY
35 V/o TUNGSTEN FIBERS

Figure . - New FRS monotape fabrication process.

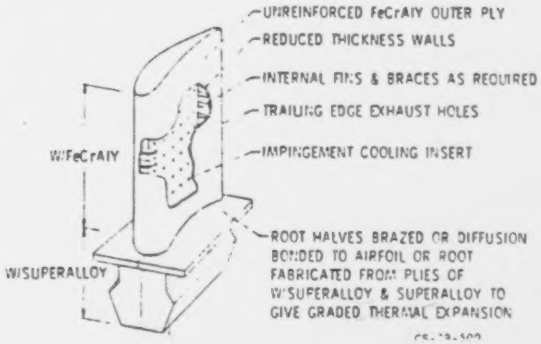
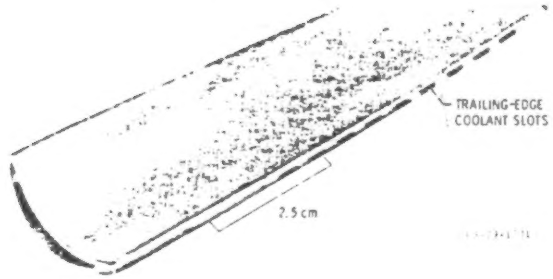

UNREINFORCED FeCrAlY OUTER PLY
REDUCED THICKNESS WALLS
INTERNAL FINS & BRACES AS REQUIRED
TRAILING EDGE EXHAUST HOLES
IMPINGEMENT COOLING INSERT
W/FeCrAlY
ROOT HALVES BRAZED OR DIFFUSION BONDED TO AIRFOIL OR ROOT FABRICATED FROM PLIES OF W/SUPERALLOY & SUPERALLOY TO GIVE GRADED THERMAL EXPANSION
W/SUPERALLOY

Figure - Schematic of FRS JT9D blade designed for fabrication feasibility experiments.

Figure A.17 (30,31)



TRAILING-EDGE
COOLANT SLOTS
2.5 cm

Figure - Composite hollow airfoil.

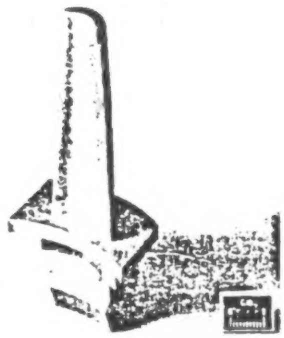


Figure . - Hollow composite blade.

Figure A. 17 (30,31)

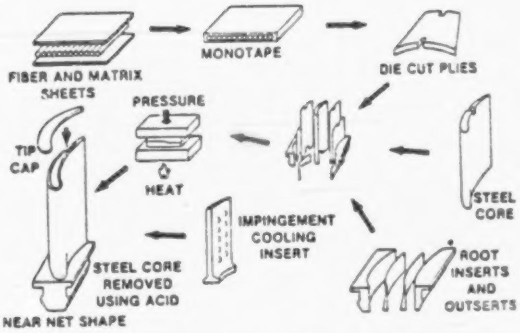

FIBER AND MATRIX SHEETS
MONOTAPE
DIE CUT PLIES
PRESSURE
HEAT
TIP CAP
STEEL CORE
IMPINGEMENT COOLING INSERT
ROOT INSERTS AND OUTSERTS
STEEL CORE REMOVED USING ACID
NEAR NET SHAPE

Figure - Schematic of TFRS fabrication process.

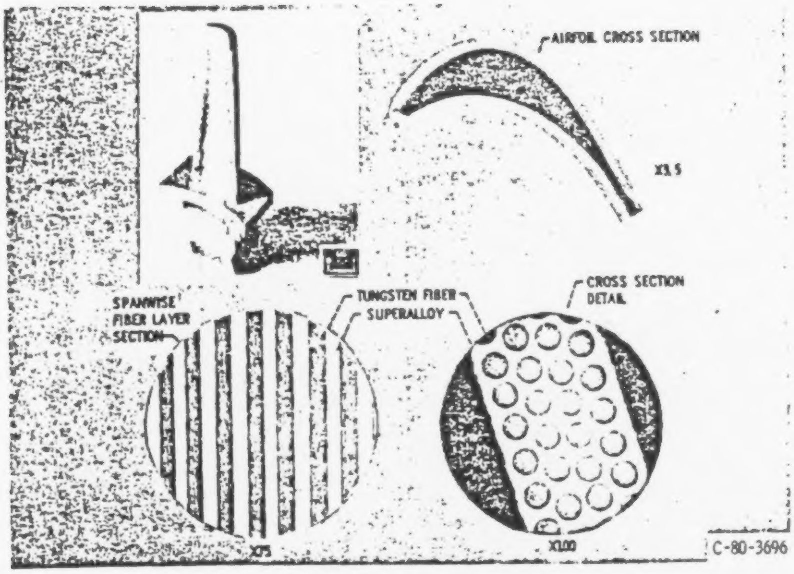

AIRFOIL CROSS SECTION
X3.5
SPANWISE FIBER LAYER SECTION
TUNGSTEN FIBER
SUPERALLOY
CROSS SECTION DETAIL
X75
X100
C-80-3696

Figure - Tungsten fiber/superalloy composite blade.

Figure A.17 (30,31)

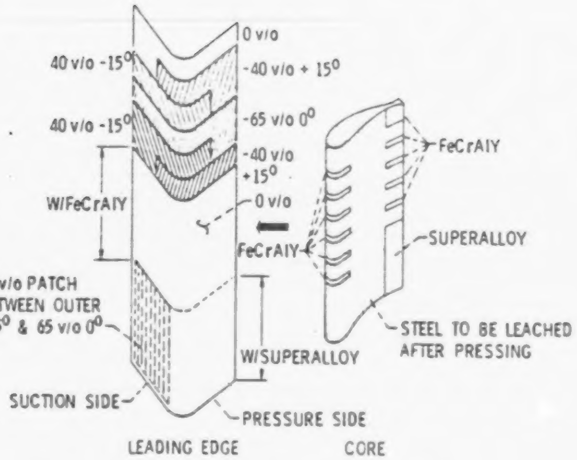

0 v/o
40 v/o -15°
-40 v/o + 15°
40 v/o -15°
-65 v/o 0°
-40 v/o +15°
W/FeCrAlY
0 v/o
FeCrAlY
FeCrAlY
SUPERALLOY
65 v/o PATCH BETWEEN OUTER -15° & 65 v/o 0°
STEEL TO BE LEACHED AFTER PRESSING
W/SUPERALLOY
SUCTION SIDE
PRESSURE SIDE
LEADING EDGE
CORE

Figure . - Schematic of airfoil ply configuration in JT9D blade.

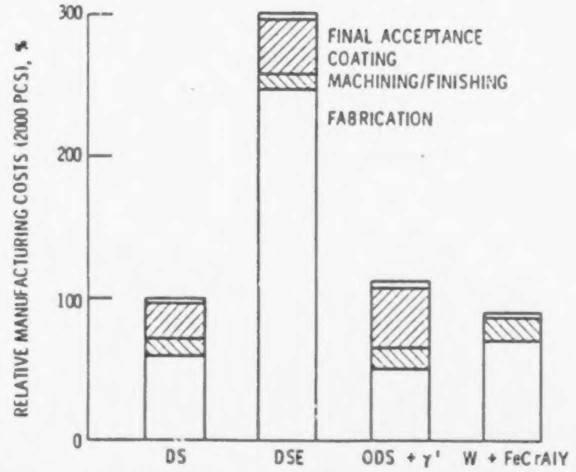


Figure - Cost analysis for JT9D first stage turbine blade.

Figure A. 17(30,31)

2.3 Carbon/Carbon (C/C) Development for High-Temperature Jet Engine Applications.

Three primary categories of jet engine applications for C/C composite technology have been identified: (35)

1. long life jet engines (transport aircraft)
2. medium life jet engines (lighter aircraft)
3. short life expendable jet engines (cruise missiles)

Aircraft engine components are expected to be exposed for long periods to temperature up to 2500° F. Cruise missile engines will be expected to have shorter exposure to turbine inlet temperatures ranging from 2500° F to 3500° F. Specific components of aircraft engines (e.g. afterburner flags and seals) are expected to survive short bursts of exposure to high temperature even over 3500° F. (Figure A.18)

The primary interest in C/C composite use in jet engines derives from its light weight, high strength and modulus at operating temperatures of interest, as well as its ability to be configured into a wide variety of component geometrics. The most significant technical barrier to the use of the composites is their susceptibility to rapid oxidative degradation at high operating temperatures.

The nearest term potential applications of C/C composites in jet engines are as afterburner flaps and seals in the Pratt and Whitney F-100 engines. Pratt and Whitney intends to carry through these technological changes

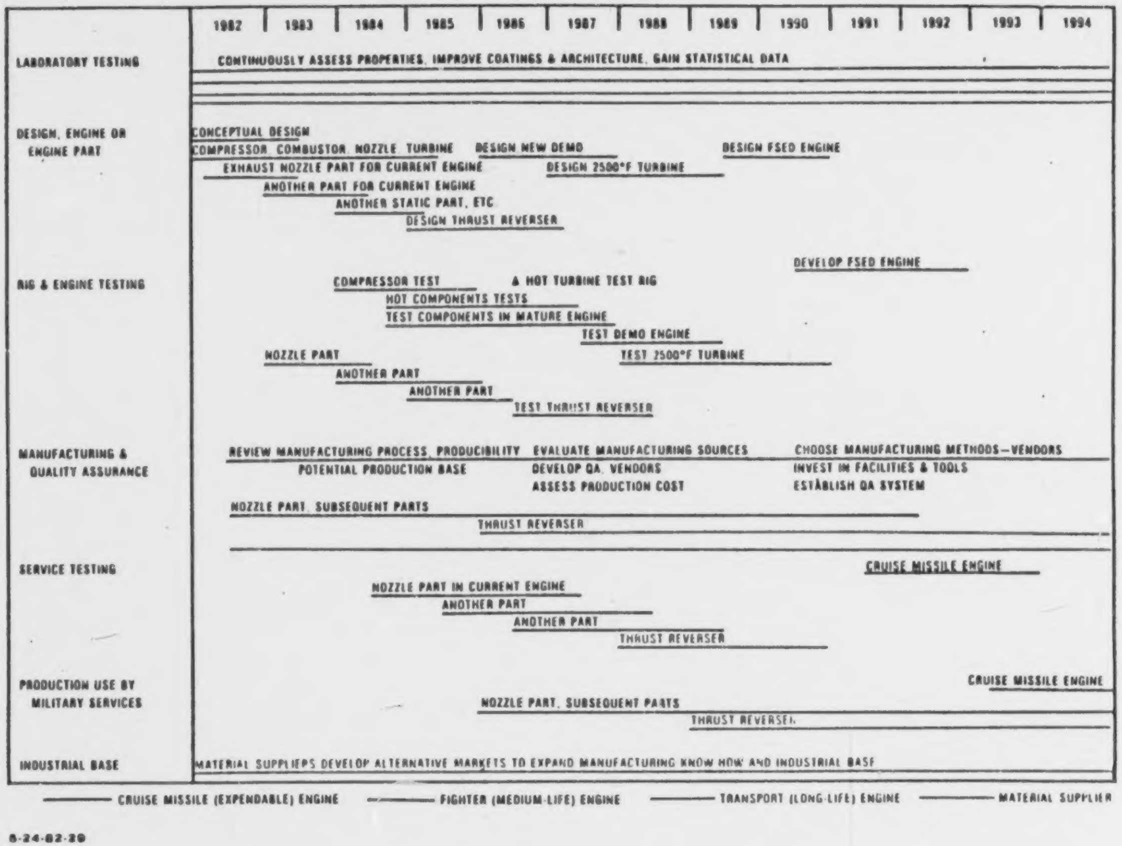


FIGURE A.18 Carbon/carbon development process for military engines. All dates, schedules, and activities are first approximations, subject to change. (35)

by 1987. Flap panels operate at up to 2500° F for less than one minute pulses in a low stress environment. In addition, static cruise missile components with gas inlet temperatures of 2500° F., including combustors, stators, nozzles and ductings, are under serious consideration for C/C application. These applications may require oxidation/coating protection (e.g. SiC). Rotating components in cruise missile or other engines application are under serious long term consideration but present a technological hurdle because of the high stress conditions (coupled with the rest).

2.3.1 Oxidation Inhibition

Much of the current developments in C/C turbine engine work has focused on providing oxidation protection at high temperatures. This includes both(1) surface and (2) subsurface coating as well as internal oxidation inhibitor systems.

C/C composite must be coated to provide protection from oxidation at temperatures above 800°C. Silicon carbide surface coatings have given good results up to 2500° F, but C/C application at up to 3500° F environment is desired. Extreme high temperatures (e.g. 3500° F.) lead to thermal expansion of the coating and development of craze cracks which may not heal upon reheat as temperature increases. Glassy materials (e.g. boron oxides, zirconium salts, silicates, tetraethylorthosilicate) are being developed to internally fill cracks that may develop, hereby inhibiting further oxidation and increasing the components usage time.

2.3.2 Surface Coating

A major effort is currently underway to provide external ceramic coatings to C/C engine turbine components. This coating serves a primary shield against oxidation of the composite in a high temperature environment. Vought's Advanced C/C composite programs relies on a SiC coating applied by a pack cementation process in parallel with an infiltration of tetraethylorthosilicate (TEOS). TEOS acts as a glass forming crack healer. Vought is also developing an electron beam ZrO_2 coating process for 3500° F use. The coatings pattern could be chosen to be columnar or not, which has the attraction that the material need not necessarily be "live-in-sight". This is of particular advantage when producing components with complex shapes. General Electric has developed three C/C coating technologies applicable to two separate operating regimes:

- Insil Process: SiC pack cementation of porous C/C followed by infiltration of the carbon matrix by molten SiC and Al_2O_3, providing protection for 2500° F-2600° F temperature range.
- Immosil Process: SiC pack cementation of porous C/C followed by infiltration of the matrix by molten molybdenum disilicide, providing

oxidation protection for the 3100° to 3500° F range.

- Wide Temperature Range (WTR) Process: This process is similar to the Insil Process but with a larger proportion of SiC, providing oxidation protection for temperatures in the range 1000°F to 3500°F. K-Karb-A, a pitch-based C/C composite fabric, has been shown to survive 200 hours air exposure time at 1200° F followed by 100 hours at 2500° F when WTR-coated. AVCO is developing C/C oxidation protection systems for static components to be used in cruise missile turbines and piping and vessels for refinery and petrochemical plants. The expected operating temperatures of these components is from 2500° F up to 3500° F. This program is in partial fulfillment of a long-range corporate goal to develop commercial oxidation resistant C/C products. Lawrence Berkely Laboratories is studying fundamental problems in the chemistry, mechanics and thermophysical interactions between coatings and the C/C composites. Specific areas of research include conversion reactions, kinetics and the influence of boron on Si in a reacting C/C system, Si and SiC oxidation, the effect of boron on viscosity, and columnar vapor deposition of ZrO_2 for a 3500° F service environments. Other groups studying C/C coating include:

- United Technologies Research Center
- Midland Materials Research
- San Fernando Labs
- Refractory Composites
- Ultracarbon
- Aerojet

These efforts do not differ substantially with the aforementioned approaches.

2.3.3 Internal Oxidation Inhibition

Acurex Corporation's C/C composite contains a transition metal which reacts during processing and is converted to a metal carbide. It may be added as a metal, a metal carbide or as a soluble organometallic compound. This system enhances the structural and oxidation inhibitory qualities of the composite: shear strengths of 4000 psi and flexural strengths of 4000 psi have been achieved, depending upon the metal compound used. Acurex has also embarked on a testing and process optimization program. Shear and torch tests are being conducted to test structural and oxidation characteristics at 2500° F; metal loaded carbon additives with SiC and Al_2O_3 coatings are the primary materials under evaluation. C/C composite with Si and B additives as internal oxidation inhibitors along with metal fiber coatings (oxygen diffusion inhibitors) are being hot spun tested with Vought. Acurex feels confident that successful engine applications will be achieved with:

High probability for a 2500° F engine
High probability for a 3000° F engine
Intermediate probability for a 3500° F engine

HITCO has integrated metal compounds within the impregnated resin polymer chain with the intention of forming surface metal carbides during the course of processing. HITCO anticipates successful turbine application in the 2200° - 2800° F. range. Their surface coating is a mixture of carbides, oxides and silicides. Both PAN and pitch precursor fibers have been tested, and it has been found that the latter oxidizes more readily. A new low pressure consolidation, uninhibited resin reimpregnation process for manufacturing turbine components appears to be the low cost solution that HITCO intends to develop.

GE has an 1 year ongoing project to develop oxidation inhibition technology via oxygen diffusion barrier layers that internally coat the composite exposed surface. C/C composites are already developed by HITCO for aircraft brake pads. The composite for this application cost between $50 to $70 per pound and it appears to be a proven technology.

Prices of C/C composite are extremely applicationdependent: a 3-D reinforced nose tip (hand laid) can cost up to $400 per pound (flyweight). Industry sources anticipate that between 15 to 200 pounds of composite, costing from $200 to $1000 per pound, could be used in jet engine applications ranging from the most simple to the most complex parts. It is anticipated that approximately 100 pounds of C/C composite would be used for the 6-inc. diameter turbine wheel and combustors in small cruise missile engines . It is not expected that engine blades will be made of C/C composite material, if only because reliability criteria for rotating high stress parts are far from met and there has been far from sufficient testing done.

3. CONCLUDING REMARKS

In 1981, 4,020 short tons of raw cobalt metal was shipped to the U.S. to derive 770 short tons for consumption in superalloys for jet engines. In that same year, 13,906 short tons of cobalt metal was imported by the U.S. in total. This indicates that 29% of raw cobalt metal imports were shipped to the U.S. for the purpose of making superalloys for jet engines, of which 6% of the total was consumed that year.

Though these numbers appear significant, all industry sources contacted have indicated that enough cobalt is or can be made available to satisfy aircraft engine demand in the event of a supply cutoff, though with a severe price penalty. The prevailing feeling is that composite materials can and will substitute for much of the superalloys currently used in jet engines, but mostly by market forces other than fear of a cutoff. The last such event in 1978 has already pushed a number of manufacturers to substitute nickel for cobalt-based superalloys and lowered cobalt demand. Jet engine manufacturers are confident that they will be able to show similar flexibility in the case of any future cut off of cobalt supply. Though active R & D efforts are devoted towards developing composite materials for jet engine applications, it is not possible at this date to make a hard estimate of the future impact this will have on cobalt-superalloy demand in the industry. Neither is it clear which engine parts will be the sites of substitutions. Major R & D funding efforts still need to be, and should be, directed towards composite materials development and testing before they can be approved for commercial or military applications.

Tungsten fiber reinforced superalloys will, in all liklihood, only be used in jet engines in the event of a crisis in the cobalt market. They have not satisfied important reliability criteria necessary for serious long-term consideration as substitutes for conventional superalloys or directionally solidified eutectics. They have not yet seen active operating service and would require a serious testing commitment before acquiring the confidence for industrial implementation.

Carbon/Carbon composites, despite their advantages in low-stress applications, cannot be expected to satisfy high temperature, high stress requirements for jet engine applications for another ten to twenty years. The implementation of these materials will be particularly sensitive to the development of oxidation inhibitors and non-destructive testing methods. While materials prices are of negligible importance when compared to the overall cost of an engine, efficient implementation of these materials in jet engines will require a major overall redesign effort which will be both costly and risky. Industry seems to believe that government risk-sharing will be necessary to promote a rapid development of these novel technologies.

Considering the likelihood of a cobalt supply cut-off, current trends in the availability of substitutes for superalloys for jet engines and the rate of development of composite materials, it is our belief that major efforts by the government to aid the development of these materials are of order, not so much as it reduces a perceived criticality of a material's supply and end-use, but as a major factor in promoting the competitiveness and supporting the long term needs of the U.S. jet engine industry.

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III. AUTOMOTIVE APPLICATIONS

Fuel economy and light weight vehicles became a vital concern of the automotive industry because of the Energy Policy and Conservation Act of 1975. CAFE (Corporate Average Fuel Economy) regulations have become a driving force behind a reexamination of automotive structures and materials. Greater use is being made of high strength, low alloy steels, aluminum and both fiberglass reinforced and non-reinforced polymeric materials in automobiles and trucks. In the longer term, especially if CAFE requirements become more stringent and downsizing less profitable in the U.S. market, automobile manufacturers will have to examine the potential of high performance advanced composites as a means of achieving significant weight reduction.

Currently, all the major automotive manufacturers have active development programs investigating the potential use of advanced composites in automotive structures, and a wide variety of prototype automotive components have been made out of advanced composite materials, including hinges, brackets, leaf springs, drive shafts, doors and door guard beams. Materials used include graphite, aramids and a variety of hybrid resin (mainly epoxy) composites.

Many of these components have been tested in actual service over the past years and have been found to perform well. Parts that are the equivalent of steel parts in performance have been built. These parts have passed a variety of laboratory tests successfully. Significant redesign has been done on each of these components to take advantage of the design flexibility which composites offer.

Ford Motor Company has publicized its interest and activity in applying advanced composite materials to automotive structures to a much greater degree than the other manufacturers. The Ford Light Weight Vehicle (LWV) program is the corner stone of its research activities in this area. The company has built an automobile that uses graphite composites to as great an extent as possible while retaining the appearance and performance characteristics of the Grenada, an intermediate size six passenger automobile. This prototype was on display at the 1979 SAE Exposition in Detroit, Michigan.

The Light Weight Vehicle has a curb weight of 2517 lbs. (1143 kg) and an inertia weight of 2750 lbs (1250 kg), corresponding to 1250 lbs (657 kg) less than the standard Grenada. Because of lower structural weight, a smaller engine, a 2.8ℓ V-6 instead of a 5.8ℓ V-8, was used without changing the vehicle's performance (0-60 mph, (100 km/hr) in 12 sec). Fuel economy (metro/highway) increased from 17 mpg for the standard Grenada to 30 mpg for the LWV. In summary, substituting graphite composite for steel in this automobile results in a 31% reduction in inertia weight and a 35% increase in fuel economy.

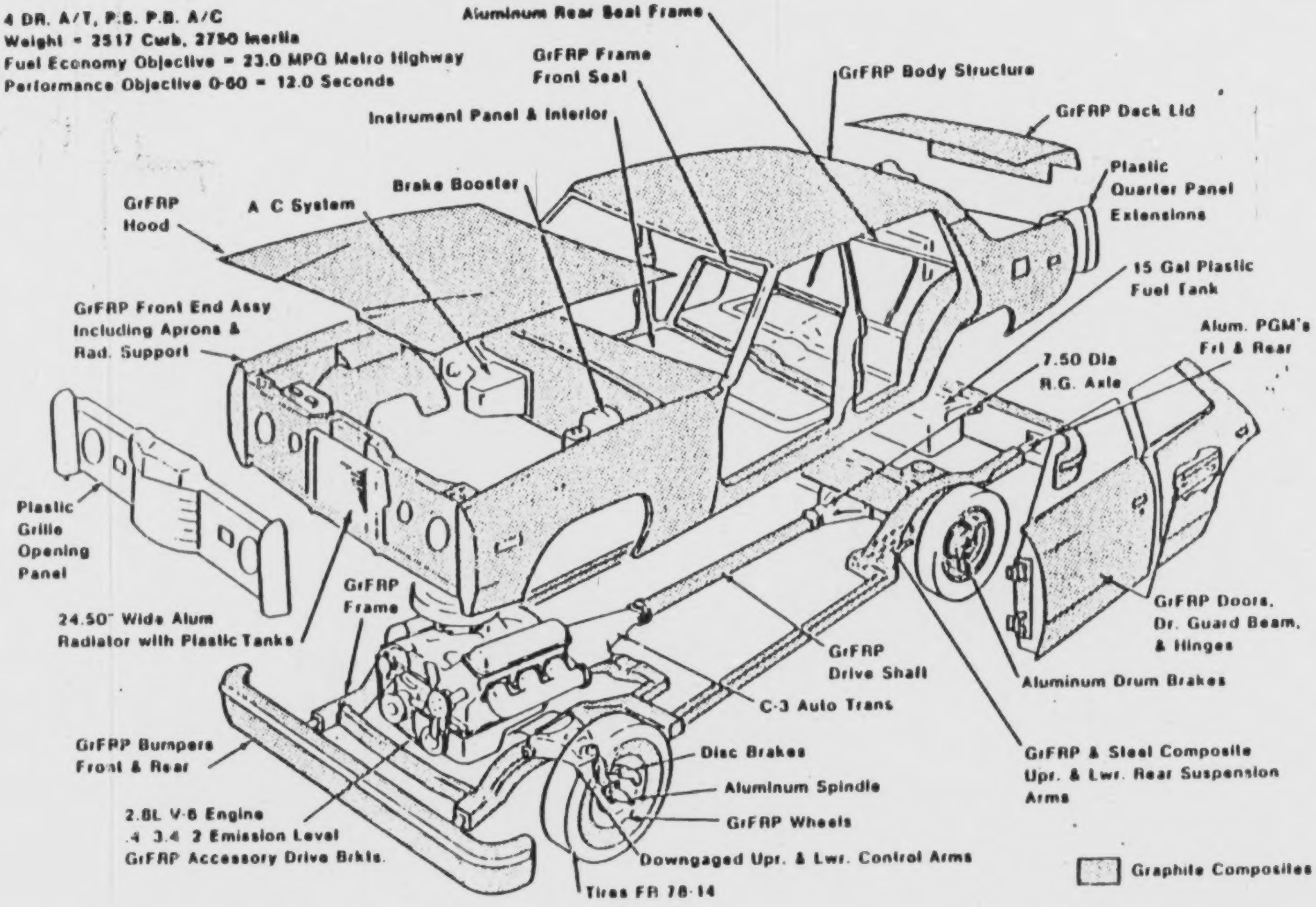
The cut-out of the LWV auto, shown in Figure B1, highlights the graphite containing components. The effect of substituting graphite composite for steel on the weight of specific components is shown in Table B1.

Ford Motor Company considers the LWV program to be both a learning and educational tool. By building most of the components of an automobile from advanced composites, Ford has learned which of these can be most readily adapted to mass production and has exposed many of the potential manufacturing problems. The program is also an educational tool in that it demonstrates to automotive designers and production engineers, both within and outside the company, that a "normal" automobile can be made from advanced composite materials. For this reason, the LWV was designed to a standard configuration, rather than to one which would make optimum use of advanced composites and which might appear "exotic" or "futuristic."

A number of problems and issues have to be addressed and solved before advanced composites are considered for substantial automotive use.

FIGURE B-1

FORD LIGHTWEIGHT VEHICLE PROGRAM



4 DR. A/T, P.S. P.B. A/C
Weight = 2517 Curb, 2750 Inertia
Fuel Economy Objective = 23.0 MPG Metro Highway
Performance Objective 0-60 = 12.0 Seconds

Aluminum Rear Seat Frame
GrFRP Frame
Front Seal
GrFRP Body Structure
Instrument Panel & Interior
GrFRP Deck Lid
Plastic
Quarter Panel
Extensions
Brake Booster
GrFRP
Hood
A C System
15 Gal Plastic
Fuel Tank
GrFRP Front End Assy
Including Aprons &
Rad. Support
Alum. PGM's
Frt & Rear
7.50 Dia
R.G. Axle
Plastic
Grille
Opening
Panel
GrFRP
Frame
24.50" Wide Alum
Radiator with Plastic Tanks
GrFRP Doors,
Dr. Guard Beam,
& Hinges
GrFRP
Drive Shaft
Aluminum Drum Brakes
C-3 Auto Trans
GrFRP Bumpers
Front & Rear
Disc Brakes
GrFRP & Steel Composite
Upr. & Lwr. Rear Suspension
Arms
Aluminum Spindle
2.8L V-6 Engine
.4 3.4 2 Emission Level
GrFRP Accessory Drive Brkts.
GrFRP Wheels
Downgaged Upr. & Lwr. Control Arms
Tires FR 78-14
▨ Graphite Composites

TABLE B1

Ford Lightweight Vehicle Program
Graphite Component Weight Summary

	Steel	Graphite	Reduction
Hood	40.0 lbs.	15.0 lbs	25.0 lbs.
Door, R.H. Rear	30.25	12.65	17.60
Hinge, Upper L. H. Front	2.25	.47	1.78
Hinge, Lower L. H. Front	2.67	.77	1.90
Door Guard Beam	3.85	2.40	1.45
Suspension Arm, Front Upper	3.85	1.68	2.17
Suspension Arm, Front Lower	2.90	1.27	1.63
Transmission Support	2.35	.55	1.80
Driveshaft	17.40	12.00	5.40
Air Conditioning, Lateral Brace	9.50	3.25	6.25
Air Conditioning, Compressor Bracket	5.63	1.35	4.28

Source: Ford Motor Company

- It would be desirable to be able to repair rather than replace large components.
- Noise Vibrations and Handling - The road handling characteristics of a large, low weight automobile are not known at the moment and it may be necessary to include load leveling provisions into the design of an automobile.
- Recycling - Reinforced thermosetting resins cannot be economically recycled at the moment, so that land fill of scrap advanced composite parts is the only current available option.
- Fabricability/mass production technologies which reduce cost and increase productivity must be devised and optimized.
- Reliability/non-destructive testing methods must still be developed.

Future development work will address itself to these issues. The average use of only 1 lb. of graphite filament per automobile will create a demand for 10 million lbs. of graphite a year. At this level, graphite could be sold for less than $10/lb. The cost of graphite (or aramid) will be further diluted by extensive use of hybrid composites. (Composite of a mixture of reinforcements, e.g. glass/graphics).

Developments over the next few years will focus on manufacturing technology and proof testing of selected components in actual service. The first use of advanced composites will be in non-safety critical parts that can be easily removed, such as an air conditioning support bracket. It is quite likely that the first production use of advanced composites by General Motors Corp. will be on a low volume, high performance model such as the Chevrolet Corvette because of the high cost of composites and so as to limit market damage in case of failure.

Over the next few years, additional advanced composite parts will be introduced for service evaluation if no difficulties are encountered in the first series. Most of these parts will be structural parts that will weigh less than 5 lbs (2.3 kg). A graphite reinforced hood or deck lid may be included to evaluate an external painted part. By 1985, there may be as many as 10 different parts in service on 10% of the vehicles produced. Assuming an average weight of 3 lbs. per part, a 20% graphite content, and the production of 10 million autos, this corresponds to a demand of 6,000,000 lbs. (273 metric tons) of graphite fiber by these automobiles in 1985.

Advanced composites usage in automobiles beyond 1985 will depend mainly on CAFE requirements imposed on the manufacturers. If these do not become more stringent than 27.5 mpg, use of advanced composites will be limited to brackets, hinges and a variety of similar small parts and these will be on a limited production basis. Additionally, several larger components may be produced from advanced composites, primarily to provide the automotive companies with internal experience in working with these materials. By 1990, the combined weight of the small components in an average car could be as much as 10 lbs. to 20 lbs. Again, assuming a 10 million car/year production rate and a 20% by weight graphite content, in these components a graphite fiber consumption of 20 million to 40 million lbs/year is envisioned.

Advanced composites will also be used to transfer automobiles from one inertial weight category to a lower one. Currently, for EPA test purposes, all automobiles that have an actual inertia weight (curb weight + 250 lbs) of 2751 lbs to 3250 lbs are grouped in the 3000 lbs. inertia weight class; those that have an inertia weight of 3251 lbs. to 3750 lbs. are grouped in the 3500 lb. inertia weight class, etc.

The corporate average fuel economy is calculated from a function which includes the inertia weight of each model in the fleet. Thus a vehicle that has an intertial weight of 3249 lbs will have a much better EPA fuel rating than a comparable vehicle that has an initial weight of 3251 lbs. The first vehicle, which will be tested in the 3000 lb class will have a rated fuel economy that is 10% higher than the second vehicle which will be tested in the 3500 lb class, and this difference could be as much as 2 to 30 mpg. If a manufacturer has a model which barely exceeds the cut-off weight for an initial weight class, it may be desirable to substitute advanced composites for heavier metal structures in this vehicle. Although this may occur at a cost penalty, the advantages of attaining a lower weight class may out-weigh the costs of substitution.

In the future, EPA will narrow the bandwidth of the inertial weight classes to 125 lbs which will reduce the incentive to drop from one weight class to another by a factor of 4. In 1985 the difference in apparent fuel economy for consecutive weight classes will be 0.8 to 1.2 mpg. Given the penalties for failing to meet CAFE ($5/automobile for every 0.1 mile CAFE), a one mpg improvement in fuel economy in a production run of 100,000 automobiles, is worth $5 million. Under these circumstances, replacing a steel component with a graphite component has a value beyond the costs of the components. A weight savings of 10 lbs/car can be construed to be worth $5/lb for each pound of weight saved.

This situation may arise in only a small percentage of the vehicles produced. Assuming the use of 30 lbs of hybrid composites to save 10 lbs of vehicle weight, on 5% of the fleet, an additional graphite usage of 3 million lbs/yr is calculated.

If the CAFE requirements become significantly more stringent than 30 mpg in the post 1985 period, then advanced composites will find much more extensive use in the automobile industry, particularly in larger luxury vehicles. Increasing the CAFE requirements will not impact the use of materials in small vehicles that are already fuel efficient. Approximately 8 to 10% of the current new car market is for luxury vehicles that sell for more than $10,000. The market for these status vehicles will continue to exist, nearly irrespective of the price of the vehicles. It is estimated that the average automobile of 1990 will consume 150 lbs of reinforced plyester plastic. It is not unreasonable to assume that the larger luxury vehicles may make more extensive use of reinforced polyester than the average car (for snob appeal and because of the market size and overall cost of the vehicle), and that the reinforcement may include significant amounts of graphite. If , for example, it is assumed that the luxury car will contain four times as much reinforced polyester composite as the average car, of 600 lbs, and that the graphite

TABLE B-2 Chromium Usage in U.S.-Built Passenger Cars Powered by Conventional Otto Cycle Piston Engines (pounds) (10)

	Actual Typical 1975 Full-Size Car (4,450 lb)	Estimated Average U.S. 1976 Car (3,750 lb)	Projected Average U.S. 1980 Car (3,000 lb)
Propulsion System			
Cylinder block, head, camshaft, valves	1.277	1.077	0.860
Cooling system	0.017	0.014	0.011
Electrical system	0.007	0.006	0.005
Carburetor, air intake, exhaust	0.118	0.099	0.079
Catalytic converter	3.335	2.587	2.070
Transmission (automatic)	0.169	0.142	0.114
Propulsion shaft, rear axle, differential	0.061	0.051	0.041
Subtotal	4.984	3.976	3.180
Chassis			
Deluxe wheel covers	1.440	1.214	0.971
Front suspension	0.250	0.211	0.169
Brakes	0.047	0.040	0.032
Steering gear	0.019	0.016	0.013
Steering wheel	0.028	0.024	0.019
Rear suspension	0.136	0.115	0.092
Lights	0.071	0.060	0.048
Miscellaneous	0.067	0.056	0.045
Subtotal	2.058	1.736	1,389
Body			
Windshield wipers	0.265	0.265	0.265
Seat belts	0.355	0.355	0.355
Windshield lower molding	0.276	0.069[a]	--
Roof drip moldings	0.203	0.171	0.137
Door window moldings	0.155	0.131	0.105
Chromium plate	0.060	0.051	0.041
Subtotal	1.314	1.042	0.903
Total chromium per car	8.356	6.754	5.472
Total without catalytic converter	5.766	4.764	3.402

TABLE B-3 Chromium Balance for Automotive Vehicles (10)

	1975	1976	1980	1985	1990	2000
Annual production of vehicles						
Otto engine	8,881,266	11,350,000	14,000,000	12,950,000	12,650,000	13,300,000
(lb Cr/vehicle — normal usage)	6.75	6.75	5.48	5.48	5.48	5.48
(lb Cr/vehicle — emergency usage)		3.08	2.46	2.46	2.46	2.46
Diesel engine — trucks	102,508 [a]	150,000 [a]	250,000	500,000	500,000	1,000,000
(lb Cr/vehicle — normal usage)			5.48	5.48	5.48	5.48
(lb Cr/vehicle — emergency usage)			2.46	2.46	2.46	2.46
Diesel engine — automobiles [b]			100,000	1,500,000	2,500,000	3,000,000
(lb Cr/vehicle — normal usage)			3.83	3.83	3.83	3.83
(lb Cr/vehicle — emergency usage)			0.39	0.39	0.39	0.39
Battery electric engine	0	0	50,000	500,000	600,000	700,000
(lb Cr/vehicle — normal usage)			2.48	2.48	2.48	2.48
(lb Cr/vehicle — emergency usage)			0	0	0	0
Total chromium in U.S. vehicle production (tons) [c]						
Normal usage	30,320	38,813	39,299	40,345	41,563	45,795
Emergency usage		14,145	17,547	16,837	16,663	18,174
Total number of scrap cars [d]	8,000,000	10,120,000	12,716,000	13,596,000	14,300,000	15,840,000
Total chromium from scrap cars (tons)						
Normal usage — 1 lb Cr/car	4,000	5,600	6,358	6,798	7,150	7,920
Emergency usage — 3 lb Cr/car		16,800	19,074	20,394	21,450	23,760
Total U.S. produced vehicle population	111,000,000	115,000,000	129,000,000	142,000,000	150,000,000	169,000,000
Total chromium used to produce service parts (tons) [e]	1,265	1,323	1,483	1,633	1,725	1,944
Total chromium used in auto industry (tons) [f]						
Normal usage	27,585	34,536	34,403	34,865	35,612	39,189
Emergency usage		- 1,332	- 44	- 1,924	- 3,062	- 3,642

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[a] Includes automobiles.

[b] Includes light trucks.

[c] Usage of Otto, diesel, and battery electric engines.

[d] Equals 88% of total Otto, diesel, and battery electric.

[e] Total U.S. produced vehicle population times 0.023 pounds.

[f] Total chromium in auto industry equals chromium in vehicle production, minus chromium from scrap cars, plus chromium used to produce service parts.

TABLE B-4 Vehicle Parts Requiring Chromium in an Emergency until Alternatives Are Developed(10)

Vehicle Parts	Pounds of Chromium Required Per Vehicle		
	1976 Car	1980 Car	1976 Diesel
Exhaust valves	0.319	0.255	0.319
Camshafts and tappets	0.087	0.070	0.087
Catalytic converters	2.587	2.070	--
Miscellaneous heat-resisting parts	0.084	0.067	0.084
Total	3.077	2.462	0.490

TABLE B-5 Emergency Chromium Reductions in Vehicles (10)

Vehicle Parts	Methods of Reducing Chromium Usage	Pounds of Chromium Reduction per Vehicle		
		1976 Car (3,750 lb)	1980 Car (3,000 lb)	1976 Diesel
Exterior trim and wheel covers	Elimination, redesign, or substitution	1.585	1.213	1.585
Seat belts and windshield wipers	Using zinc or Cu-Ni-Cr plate on plain steel in place of stainless	0.620	0.620	0.620
Suspension springs	Using a non-chromium spring steel instead of 5160	0.326	0.261	0.326
Cylinder blocks, heads, and other iron castings	Substituting other alloying elements for chromium	0.617	0.537	0.862
Gears, ball and roller bearings, and other chromium alloy steel parts	Substituting another alloy without chromium	0.480	0.384	0.480
Total chromium reduction		3.682	3.015	3.844

TABLE B-6 Total Chromium Content (pounds) in Various Engines[a] (10)

Materials	Present Piston Otto, 150 hp	Present Diesel, 150 hp	Battery Electric, 50 mph, 4 Passenger	Free Turbine Brayton, 150 hp		Single-Shaft Brayton, 150 hp		Stirling, 170 hp			Rankine, 150 hp	
				Mature	Advanced	Mature	Advanced	Present	Mature	Advanced	Mature	Advanced
Chromium-Containing												
Super alloy				2.33		0.77		12.15	1.50		1.65	
Stainless steel	2.905	0.319	0	5.40	3.25	4.19	1.61	28.8	14.94		30.6	4.14
Alloy steel	0.014	0.014	<.01	0.08	0.06	0.08	0.06	0.22	0.08	0.07	0.12	0.12
Cast iron	0.735	0.949[b]	0	0	0	0	0	0	0	0	0	0
TOTAL Chromium	3.654	1.282	<.01	7.81	3.31	5.04	1.67	41.17	16.52	0.07	32.37	4.26
Other												
Ceramic				20	112	20	106	22	22	110	–	93
Aluminum								51	181	178		
Cobalt				3.9		0.60			2.2		2.2	
Tungsten				6.80		0.75			0.37		0.27	

[a] Engine ready to run less transmission and battery.

[b] The diesel is assumed to have head, block, and bearing caps weighing 1.35 times the Otto. Other castings are the same.

NOTE: Based on data from Jet Propulsion Laboratory, 1975.

content is 20%, the larger vehicles would contain an additional 120 lbs of graphite filaments. This would add $800 to $1000 (constant dollars) to the cost of the car. While this added cost would be prohibitive in an average $6000 automobile, it could be considered in a $12,000 status vehicle. A million luxury automobiles a year, each containing 120 lbs of graphite filament, would consume a total of 120 million pounds of graphite filaments a year.

The truck and bus market is a derivative market of the passenger automobile market. Because of the lower production rates, and the direct economic value of weight savings to the purchaser, advanced composites may be introduced into truck production more readily than automobile production. The same general components that would be used on automobiles would also be used on trucks.

To date, chromium uses in cars include functional (32 lb/car) and decorative (9.5 lb/car) stainless steel, chromium plate and alloys in steel and cast iron. Much of this is recycled (e.g. offal from stainless steel stamping, iron and steel turnings, junk scrap parts). Some foundries obtain as much of their chromium by recycle. Also, already 1 to 3 pounds per car could be recovered from junk scrap. The following Tables show typical data of chromium usage in automobiles in the U.S.

Tables B-2 to 6 show average chromium usage in automobiles. broken down into a number of components. Some of the latter are already under consideration by the industry to be substituted for by composite materials. In some cases, prototypical component parts have been manufactured and even seen commercial application:

- Cylinder blocks: could be made of Alumina-SiC/ Aluminum composites. Some auto manufacturers are aleady seriously considering reintroducing aluminum cylinder blocks into production.

- Cylinder heads: same as above. Merceedes and Porsche use Reynolds 390 in air cooled engines. These materials may be reinforced, to reduce matrix volume content.
- Cooling system: Aluminum 1100, 1145, 3003, 5005, 7072 and 8007 are all potential alternatives to chromium containing materials. These aluminum alloys contain no significant amounts of chromium themselves and could be reinforced with SiC-Aluminum whiskers or fibers.

- Carburetor and air intake: Both have been made of injection molded PBT matrix and glass fibers (experimental prototypes).
- Propulsion shaft: Drive shafts for rear wheel drive automobiles and trucks have been made from graphite/glass epoxy composites by filament winding.
- Front and rear suspension: Corvette springs have already been successfully made out of glass/epoxy composite materials.
- Steering wheel: could also be made out of a glass/epoxy composite.
- Windshield Wipers: Wiper arms could be compression molded or injection molded from several types of composite including glass/polyester or glass/nylon.
- Deluxe wheels covers, windshield, roof and windows moldings and chromium plate:

The use of chromium in these applications is motivated by aesthetic reasons and it could easily be replaced by aluminum or another material in the event of a chromium shortage.

- Exhaust values: could be made of fiber reinforced iron-based superalloys or possibly, graphite reinforced polyimides.
- Camshafts, tappets, valves and valve seats: graphite reinforced epoxy parts have already been used in racing cars, but have not been used on commercial vehicles because of cost and reliability considerations.

A new program by Toyota of Japan to develop ceramic fiber reinforced aluminum pistons for high performance diesel engines may be paving the way for renewed interest in advanced engineering metal-matrix composites for substitution of traditional materialsin high temperature/high stress automotive applications. The recently tested pistons have been shown to exhibit higher wear resistance, seizure resistance against cast iron, thermal conductivity and strength at high temperatures.

Irrespective of reducing the chromium content of these parts, potential overall advantages of fiber strengthened piston top lands and top ring grooves include fuel saving, increased horsepower, and reduced exhaust emission.

Toyota has tested four reinforcement fibers:

- Titanate (high strength and stiffness, small diameter)
- Carbon (low specific weight, good strength and stiffness, large diameter)
- Alumina-Silica (good strength, medium stiffness, small diameter)
- Alumina (same as above)

Of these, the alumina and alumina-silica best satisfied strength, wear resistance and cost constraints.

Test results showed that all reinforced alloys were more wear resistant than SAE321 aluminum alloy, particularly with Alumina-Silica and Alumina reinforcement. Similar results were observed for seizure resistance.

Overall results indicate that Alumina/Aluminum and Alumina-Silica/Aluminum composites offer the best improvement in piston performance. Based on this research, Toyota is using composite pistons in some 1983 production diesel engine.

The following tables and figures show typical results of the Toyota study.

It will be important to watch the market's reception of the 1984 GM Fiero. It could signal the onset of a new tide of acceptance of plastic materials in automobiles. Fiero's SMC and reinforced RIM (Reaction Injection Molded) urethane exterior panels - the first all-plastic installed on a large volume car - offers corrosion resistance, durability and improved mileage (from a lighter weight). Overall, the Fiero uses 240 lbs. of plastics, including front and rear facia, bumpers and springs. Assembled around a modular steel frame, all attachment points are simultaneously milled and drilled in a single computer controlled pass through a Gillman maching unit.

GM claims this technology is competitive versus steel for quantities of up to 100,000 units per year. This seems to be a first indication that the industry sees the economics increasing in favour of mass-produced plastic automotive parts.

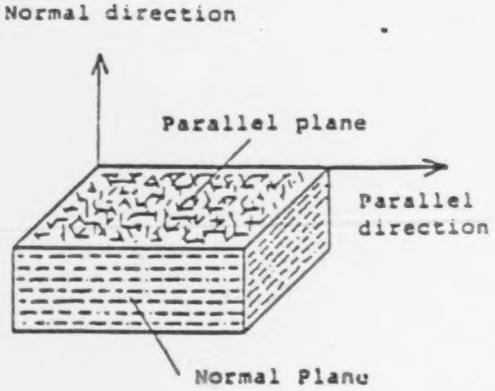
Normal direction
Parallel plane
Parallel direction
Normal Plane

Fig. 1 - Fiber orientation and direction of FRA

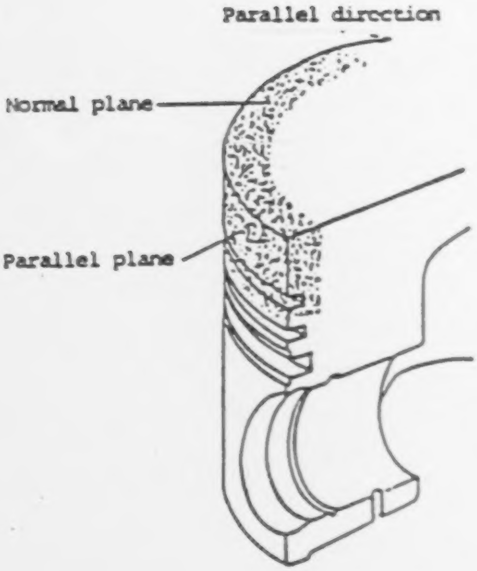
Parallel direction
Normal plane
Parallel plane

Fig. 2 - Fiber orientation of CFA reinforced piston

Table 1 - Physical properties of reinforcing fibers

Fiber	Composition	Diameter (μm)	Density (g/cm³)	Strength (MPa)	Modulus (MPa)
Titanate	$K_2O(TiO_2)_6$ Whisker	0.2	3.3	>7,000	280,000
Carbon	Pich carbon	12	1.6	1,100	60,000
Alumina-Silica	Al_2O_3 : 51% SiO_2 : 49%	2.8	2.6	1,300	120,000
Alumina	Al_2O_3 : 95% SiO_2 : 5%	3.0	3.4	1,000	100,000

Table 2 - Description of fiber reinforced aluminum alloy

Composite	Fiber	Matrix	*V_f (%)	Density (g/cm³)	**H.T.
T-Al	Titanate	SAC321	9.8	2.8	T6
CC-Al	Carbon	SAC321	6.9	2.6	T6
AS-Al	Alumina-Silica	SAC321	6.6	2.7	T6
A-Al	Alumina	SAC321	4.7	2.7	T6

*V_f : Volume fraction of fibers **H.T. : Heat treatment

Table 3 - Description of Ceramic Fiber Alloy

Ceramic fiber alloy	Fiber			Fiber V_f (%)	Hardness of FRA (Hv 10kg)
	Al_2O_3 (%)	SiO_2 (%)	*A.D. (μm)		
A-Al	94 ~ 97	3 ~ 6	2.0 ~ 4.5	3.5 ~ 5.5	100 ~ 150
AS-Al	44 ~ 50	50 ~ 56	2.0 ~ 4.5	6.0 ~ 8.0	85 ~ 140

*A.D. : Average diameter

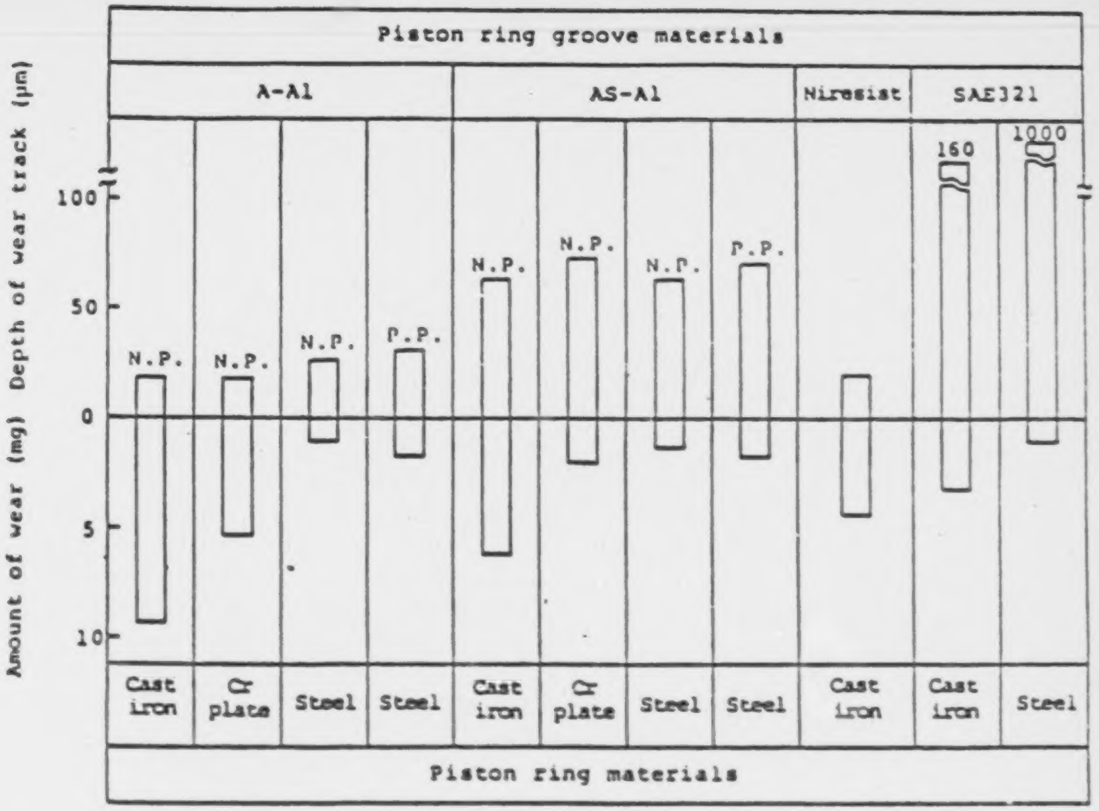

Fig. 3 - Wear properties of CFA against piston ring materials

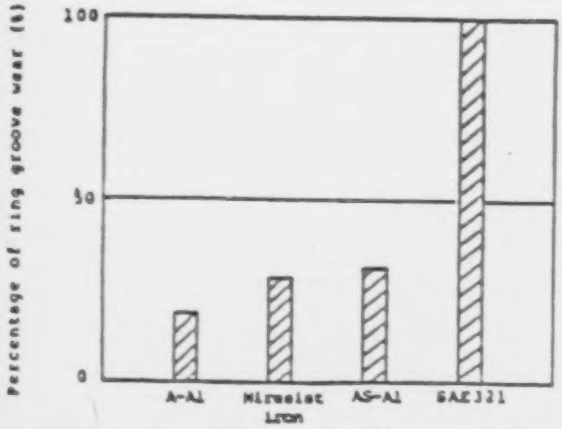

Fig. 4 - Comparison of ring groove wear charactaristics

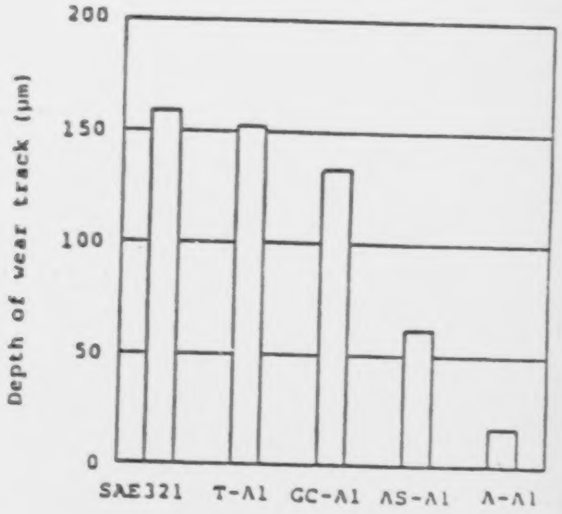

Fig. 5 - Wear resistance of FRA against piston ring material (S.G. cast iron)

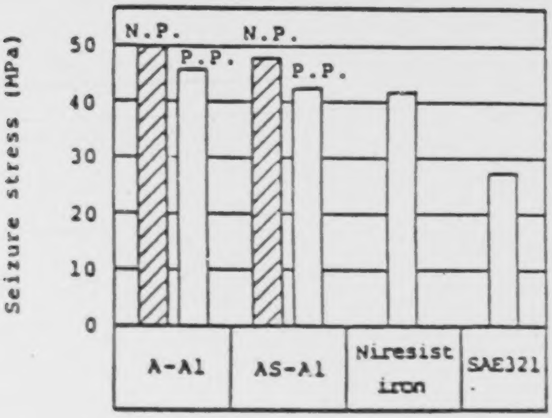

Fig. 6 - Seizure stress of FRA against cylinder bore material (LAG iron)

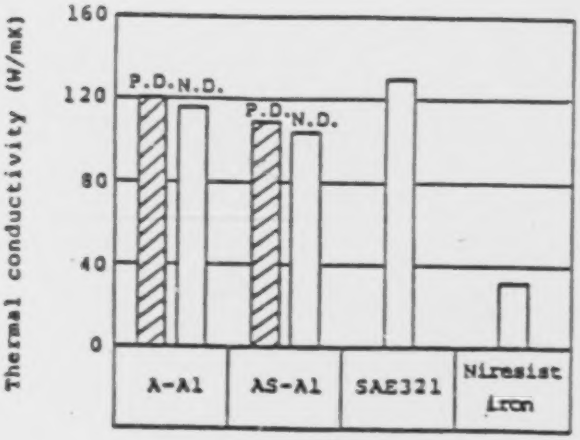

Fig. 7 - Thermal conductivity of CFA

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IV. OIL/GAS DRILLING EQUIPMENT APPLICATIONS

The opportunities for advanced composition in oil and gas drilling and production equipment is significant, although its development has been slow. The oil/gas drilling and production industries have been reluctant to back major efforts in composites technology because of the high cost and high risk associated with well development ("rigtime" for a 2000 foot gas well in Louisiana can cost \$5 - \$10 million).

Drilling and piping equipment for deep oil and gas exploration can be exposed to severe high temperature (e.g. 900°F), high pressure (up to 22 kpsi), corrosion (up to 75% H_2S, or seawater) and wear. To date, superalloy materials (e.g. stellite) have been used to service in these environments. Demand for these materials increased with the development of enhanced oil recovery technologies(e.g. steam of CO_2 flood), which increase the severity of the operating environment. However, the current drop in oil prices has reduced both the momentum behind enhanced oil recovery and "difficult" well development.

Nevertheless, under current conditions, lightweight, corrosion and wear resistant materials are desirable in oil/gas equipment to reduce stresses on inner production tube strings. A potential exists for metal matrix composites (e.g. reinforced aluminum) for drill bits and downhole-pump parts. There exists also the potential for widespread use of fiberglass tubing for pump ("sucker") rods linking the surface to downhole pumps and for production tubing strings inside steel casings. Fiberglass tubings have seen a limited use in the field, though high cost has limited development. A serious committment by the major oil companies will be necessary before widespread use of composite technologies will occur.

V. SUMMARY

This study analyzes the substitutability of advanced engineering composites for critical materials (e.g. chromium, cobalt, manganese.) The study focuses primarily on two particular areas: jet engines and automotive applications, accompanied by a primer covering the major advanced engineering composite materials, their properties, fabrication technologies and prices. In the jet engine section, an in-depth analysis of jet engine technology, traditional materials usage, working environment and specific current composite materials applications is provided. In the automotive section, a general overview of recent and potential advances in composite materials usage in the automotive sector is provided.

For this study, a composite is considered to be any rigid man-made structural material in which a filamentary reinforcement is embedded in a binding matrix yielding a material with physical properties that exceed the properties of its constituents taken alone. Composites are classified according to their matrix material which is either polymeric, metallic or ceramic. Of these three, polymeric composites are the most highly developed, with successful commercial applications dating back to the 1940's. Currently, there is only one commercial application of metal matrix composites (Toyoto Motor Co.) and there are no applications of ceramics.

The unique advantages of composite materials include design flexibility, high specific properties (properties per unit weight), and good chemical and corrosion resistance. Some of the cited disadvantages of composites are high cost, (especially of the reinforcing filaments), low ductility, poor repairability, lack of design data and experience, and poor productivity in fabrication.

JET ENGINES

In the aerospace industry, cobalt and chromium have been identified as strategic materials. The role of composite materials in the hot section of turbine jet engines was investigated with respect to engineering and economic feasibility. The objective was to analyze the potential for a reduction in dependence of U.S. military and civilian engine industries on critical materials.

The need for these superalloys have seen increased application due to increasing demands on performance, durability and fuel efficiency of jet engines in a competitive world market. The fabrication of superalloys for jet engines consumed 37% of all the cobalt used in the U.S. in 1982. Although chromium consumption in superalloys represent approximately 5% of total domestic use, no feasible engineering substitutes are known to exist.

Since cobalt and chromium are used in jet engines for the heat and corrosion resistance they impart, most composite materials such as glass, graphite, polyimide and thermoplastic cannot be considered for direct substitution. The primary impact of these composites in the aerospace industry will be indirect. The use of these materials to reduce the weight of stationary, low temperature component applications will cascade into downsizing the high stress, high temperature components, thus reducing the need for superalloys. It is unlikely that wholesale substitution of advanced engineering composite materials for superalloys will occur in the absence of a national emergency. Composite materials are expected to make gradual inroads into the jet engine industry due to market forces alone (e.g. prices, cost reduction advances in performance characteristics) over the next decade. However, two likely candidates for direct substitution of composite materials for superalloys in the hot section of jet engines are metal matrix and carbon/carbon composites.

One type of metal matrix composite, fiber reinforced superalloys, has been shown to meet many of the property requirements of high stress, high temperature components in the hot section of jet engines. Although they would not eliminate the usage of superalloys, they could substantially reduce the amounts used while improving some of the performance characteristics of the engines.

Tungsten wire reinforced iron-based superalloys (W-FeCrAlY) are the most promising candidates to date for turbine blade, vane and disk applications. W-FeCrAlY has been shown to exhibit superior stress-rupture strength, creep resistance, high, low and thermal fatigue resistance, impact strength and thermal conductivity. The main drawback of W-FeCrAlY is that tungsten, exposed to the jet engine environment following erosion of the superalloy, would be highly vulnerable to attack. This could lead to catastrophic failure of the part. Another problem is the high density of tungsten which considerably increases the weight of the part. Nonetheless, the successful application of W-FeCrAlY in jet engines would substantially reduce the use of cobalt in jet engines at a cost comparable to that of the newly-developed directionally solidified alloys.

Carbon/Carbon (C/C) composites have undergone rapid development over the last decade, largely spurred by potential aerospace and military applications. A large effort is currently being devoted to the adaptation of C/C composites to high temperature/low stress sections of gas turbine engines for manned aircraft applications (e.g. after-burners in P & W F-100 engines) and in high stress/high temperature sections of unmanned aircraft engines (e.g. cruise missile components.)

C/C composites have distinct advantages over traditional materials in their light weight, high strength and modulus, in their heat resistance, wear resistance and their ability to be configured into a wide variety of component geometrics. However, oxidation of C/C composites is the primary barrier to successful implementation of these materials in jet engines. Substantial efforts are currently being devoted by government and industry to the development of surface coatings and internal oxidation inhibitors which permit operating temperatures in excess of 3000°F. Industry sources anticipate that high temperature/low stress jet engine components will be available within five to ten years. High stress components will take much longer to develop.

AUTOMOTIVE

The quantities and variety of materials used in the automotive industry are enormous. Materials and fabrication processes that provide parts must be cost-effective, energy conserving, functional and aesthetically pleasing. Satisfying these constraints, though, do not guarantee acceptance by the industry. Market timing requirements, quality assurance and adequate production capability to satisfy demand must all be met before the industry will seriously consider the vast investments necessary to bring an innovative concept to the marketplace.

Since production processes and tooling could be adjusted to the quantities needed, reinforced plastic materials have quickly gained industry acceptance for low-volume applications designed to satisfy specific market segments. Designs could be quickly changed when a competitive advantage was recognized. Low tooling investments and relatively short design-to-production lead times reduced total risk.

Within the last ten years, CAFE regulations have provided a driving force behind a revaluation of automotive structures and materials. Weight savings in any vehicle part can reduce size and cost of many other support, restraint, acceleration/decelleration and containment components of a vehicle, up to a limiting tradeoff (cost vs. weight saved) level.

The ease of fabrication and versatility of reinforced plastics production processes and properties offer a wide variety of potential product designs. Reinforced plastics can replace many cast, forged and extruded automotive parts while offering superior weight savings and corrosion resistance, as well as good impact and fatigue resistance. For example, automobile hoods and fenders have already been successfully produced and have received customer approval. It is anticipated that in the near future most exterior body parts will follow suit, (witness the recently marketed GM Fiero.) One of the primary advantages of this scenario is the potential for dramatically reduced assembly cost, because of a reduction in the number of components involved and the subsequent increased applicability of automation technology.

U.S., Japanese and European automobile manufacturers are pursuing active research efforts towards the introduction of high temperature carbon fiber reinforced plastics, metal matrix and reinforced ceramic composites in high stress, high temperature engine and drive train components of automobiles. While most of these technologies are still in the experimental and developmental stages, it is anticipated that these applications could, in the future, further reduce the reliance of the automotive industry on high chromium and manganese-content ferrous materials (e.g. stainless steels.) Though fabricated components may be technically good, it is difficult to precisely define their production cost impact at this point.

CONCLUSION

Metal and ceramic composites offer great potential for reducing U.S. dependence on critical materials, especially cobalt and chromium. Cobalt and chromium are used primarily as alloying elements in high temperature metals (i.e. superalloys.) Metal and ceramic composites are being developed which can maintain their physical properties at temperatures in the range of 1500° to 3000°F. Once developed, these composites will be a viable substitute for chromium and cobalt bearing superalloys.

Composite materials can be expected to reduce the nation's dependency on imported critical materials. However, it is doubtful that this reason will be the driving force behind their further development. Rather, the unique advantages of these materials will spur their development. (Of course, in the event of a supply disruption, availability will become a distinct advantage.) Manufacturers will rarely elect to use an expensive material in an application which can be satisfied with a less expensive, available, but "critical" material.